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Mineral Resources Potential of Antarctica

**John F. Splettstoesser
Gisela A. M. Dreschhoff
Editors**

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John F. Splettstoesser and Gisela A. M. Dreschhoff Editors

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The Antarctic Research Series: STATEMENT OF OBJECTIVES

The Antarctic Research Series, an outgrowth of research done in the Antarctic during the International Geophysical Year, was begun in 1963 with a grant from the National Science Foundation to the American Geophysical Union. It is a book series designed to serve scientists, including graduate students, actively engaged in Antarctic or closely related research, and others versed in the biological or physical sciences. It provides a continuing, authoritative medium for the presentation of extensive and detailed scientific research results from Antarctica, particularly the results of the United States Antarctic Research Program.

Most Antarctic research results are, and will continue to be, published in the standard disciplinary journals. However, the difficulty and expense of conducting experiments in Antarctica make it prudent to publish as fully as possible the methods, data, and results of Antarctic research projects so that the scientific community has maximum opportunity to evaluate these projects and so that full information is permanently and readily available. Thus the coverage of the subjects is expected to be more detailed and extensive than is possible in the journal literature.

The series is designed to complement Antarctic fieldwork, much of which is in cooperative, interdisciplinary projects. The Antarctic Research Series encourages the collection of papers on specific geographic areas within Antarctica. In addition, many volumes focus on particular disciplines, including marine biology, oceanology, meteorology, upper atmosphere physics, terrestrial biology, geology, glaciology, human adaptability, engineering, and environmental protection.

Topical volumes in the series normally are

devoted to papers in one or two of these areas. Annual volumes, an innovation in 1990 to encourage rapid publication, can contain papers in any discipline. When needed, the series utilizes special formats, such as maps. To reach the most appropriate community, papers approved for the Antarctic Research Series may be published in any of the monographs or serials issued by the American Geophysical Union.

Priorities for publication are set by the Board of Associate Editors. Preference is given to research manuscripts from projects funded by U.S. agencies, long manuscripts, and manuscripts that are not readily publishable elsewhere in journals that reach a suitable reading audience. The series serves to emphasize the U.S. Antarctic Research Program, thus performing much the same function as the more formal expedition reports of most of the other countries with national Antarctic research programs.

The standards of scientific excellence expected for the series are maintained by the review criteria established for the AGU publications program. Each paper is critically reviewed by two or more expert referees. A member of the Board of Associate Editors may serve as editor of a volume, or another appropriate researcher may be appointed. The Board works with the individual editors of each volume and with the AGU staff to assure that the objectives of the series are met, that the best possible papers are presented, and that publication is achieved in a timely manner.

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BOARD OF ASSOCIATE EDITORS
Antarctic Research Series

PREFACE

Interest in the potential mineral resources of Antarctica has been expressed throughout the history of exploration of the continent. This volume of the Antarctic Research Series results from an attempt to assemble a summary of current factual knowledge and scientific data related to issues of mineral resources in Antarctica.

At the First International Symposium on Antarctic Geology, held in Cape Town in 1963, no papers were presented on economic minerals in Antarctica, although in one paper, by Mueller (in *Antarctic Geology*, edited by R. J. Adie, pp. 393–394, North-Holland, Amsterdam, 1964), the author mentioned mineralized locations in the Antarctic Peninsula, and in another paper, by Stewart (published in the same book, pp. 395–401), a list of 222 minerals known from the Antarctic was tabulated mainly as an inventory of all minerals that had been reported at that time.

At the Second Symposium on Antarctic Geology, held in Oslo in 1970, Neethling (in *Antarctic Geology and Geophysics*, edited by R. J. Adie, pp. 554–555, Universitetsforlaget, Oslo, 1972) pointed out the economic significance of the proximity of South Africa to Antarctica in Gondwanaland reconstruction. At the Symposium on Antarctic Geology and Geophysics, held in Madison, Wisconsin, in 1977, a collection of four chapters appeared for the first time at any of these symposia under the heading of “Mineral Deposits” (*Antarctic Geoscience*, edited by C. Craddock, pp. 853–883, University of Wisconsin Press, Madison, 1982). At the Fourth International Symposium on Antarctic Earth Sciences, held in Adelaide, South Australia, in 1982, a series of seven chapters appeared under the heading “Antarctic Resources” (in *Antarctic Earth Science*, edited by R. L. Oliver et al., pp. 413–437, Australian Academy of Science, Canberra, 1983).

C. Craddock organized a session on “Antarctic Resource Potential” at the 1979 annual meeting of the American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, in Houston, Texas. Eight papers were given in a half-day session by some of the authors in this volume. This meeting, in fact, provided the stimulus for a volume on the subject of Antarctic resources, which, after several delays and a change of publishers, has now come to fruition.

This volume includes not only papers that are the culmination of many years of research conducted in

Antarctica by leading scientists, but also additional studies by specialists from the United States, Australia, Federal Republic of Germany, South Africa, and the United Kingdom. The first two papers are intended to provide an overview of the geologic setting and history of the Antarctic continent. The next seven papers lead directly into differing aspects of various potential mineral resources in Antarctica. These individual papers are the result of basic and detailed geologic work as well as reconnaissance resource evaluation, such as the paper on uranium distribution. The next three papers discuss coal and hydrocarbons, followed by papers on freshwater resources and manganese. The current logistics program of the United States has been used as an example of the possibilities and difficulties facing operations on the icy continent. Tourism has also been included as a resource within the framework of environmental impact. Finally, the political questions have been addressed, and, furthermore, the report “The Antarctic Minerals Convention” by Lee Kimball (1988) has been reprinted in full and added to this volume. Kimball’s report has not been reviewed and is included in order to make more widely available a discussion of the provisions of the Convention on the Regulation of Antarctic Mineral Resource Activities.

The International Geophysical Year (IGY), 1957–1958, was the beginning of the era of global cooperative scientific research programs and included a major emphasis on Antarctica, with 12 nations establishing 60 research stations (National Science Foundation, Facts About the U.S. Antarctic Program, OMB 3145-0058, 1988). Since then, the large scientific data base has been accumulated not only through great personal commitments and hardships in fieldwork, but also through exceptionally high expenditures by the individual nations that fund and support research in Antarctica.

The collection of scientific data has been performed under the auspices of the Antarctic Treaty. The provisions of the Treaty were originally negotiated in 1959 by the 12 IGY nations active in Antarctica, and entered into force in 1961. It establishes the legal framework for the area south of 60°S (National Science Foundation, Facts About the U.S. Antarctic Program, OMB 3145-0058, 1988). Among other provisions it freezes all political claims, provides for free access across the Antarctic continent for scientific research, and promotes the free exchange of scientific data. There is no time limit on the

Treaty, only a designated period of 30 years that must elapse before it can be considered for review, in 1991, if called for by one of the consultative parties to the Treaty. If no review is called, the Treaty will continue without interruption or change. Even if a review conference is convened, it may not result in any changes or amendments to the Treaty.

Consultative meetings, provided for by the Treaty, have resulted in the adoption by the Treaty Nations, and entry into force, of a number of conservation conventions. However, not until 1981 did the Treaty Nations propose convening a special meeting to initiate negotiations on a convention to establish a framework of rules and regulations for minerals development in Antarctica in advance of any prospect of such activity. The minerals negotiations were launched at the IV. Special Antarctic Treaty Consultative Meeting (ATCM) in 1982. By the time the minerals convention was adopted, the number of countries that had gained consultative status in the Antarctic Treaty System had increased to 20. Most nations, at the time of writing, have yet to ratify the Convention on the Regulation of Antarctic Mineral Resource Activities, or CRAMRA, which was adopted in June 1988 and opened in November 1988 for signature and, in due course, ratification.

The papers in this volume provide a basis for a partial assessment of the mineral potential of Antarctica. Mineral deposits having proven economic values have not been discovered anywhere in Antarctica or its continental shelf. This is in part due to the moratorium on resource activities imposed by the Antarctic Treaty nations and in part due to the inherent difficulties in mineral resource evaluation stemming from the physical setting. The latter relate in large part to the extensive ice cover (98%) on the continent; the climate and the logistic problems that are caused by it effectively pre-

vent yearround activities except in the most northerly latitudes. The Antarctic continent is surrounded by a wide band of drifting pack ice and icebergs that varies dramatically in size between winter and summer. During the winter the sea ice expands to such an extent that the ice-covered area of the south polar region doubles in size. During the summer the existence of open seas extending to the coastline, wide leads in pack ice, and the unpredictable effects of katabatic winds have often been deceiving, and a number of ships, ice strengthened or even classified as icebreakers, sustained severe damage or sank in recent years. For these reasons, in many areas of Antarctica the costs of developing and exploiting resources, mineral or hydrocarbon, could easily exceed the value of the recovered commodities. It is difficult to predict when world markets and depletion of scarce commodities might lead to mining for metals or when the production of gas and oil might become economic.

In this volume we have attempted to present a balanced view so that possible future activities take into account the known hazards as well as any potential rewards. Those who have had the privilege of working in Antarctica realize that its extraordinary natural beauty is one of the resources of greatest value, and many feel as strongly as Laurence M. Gould, geologist and second-in-command of the first Byrd Antarctic Expedition, 1928–1930, who wrote in his book *Cold: The Record of an Antarctic Sledge Journey* (first published by Brewer, Warren and Putnam, New York, 1931, and reissued with additional material by Carleton College, Northfield, Minnesota, 1984) “And I had rather go back to the Antarctic and find a fossil marsupial than three gold mines!” The fossil marsupial has since been found, but the gold mines have not.

John F. Splettstoesser and Gisela A. M. Dreschhoff

THE MINERAL RESOURCES OF GONDWANALAND

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This introductory paper, understandable to lay readers, is a short summary of the mineral resources of Gondwanaland; it offers a basis for expecting the existence of mineral resources in Antarctica. Geological and geophysical evidence strongly suggests that South America, Africa, Madagascar, peninsular India, Antarctica, Australia, and New Zealand were joined together as the supercontinent Gondwanaland through a long interval of geologic time until its fragmentation began, probably during the Jurassic period. While some problems remain, a generally satisfactory reassembly of Gondwanaland can be made. Antarctica is the centerpiece in this reconstruction, but its mineral resources are poorly known. Important deposits of metals and precious stones occur across Gondwanaland. Iron deposits are found in South America, Africa, India, Australia, and Antarctica, mainly in Precambrian sedimentary iron formations. Base metals and precious metals are mined in South America, Africa, India, and Australia, occurring in veins, in extrusive or intrusive igneous rocks, or in sedimentary placer deposits. Diamonds have been found in igneous pipes in Africa and Australia, and precious stones are recovered from high-grade metamorphic terranes, as in Sri Lanka. Gondwanaland holds important resources of mineral fuels. Oil or gas fields have been discovered in South America, Africa, India, Australia, and New Zealand. The hydrocarbon accumulations found to date on the shield areas are modest, but significant fields occur in (1) young deformed belts around the edges of Gondwanaland and (2) young basins associated with the fragmentation of Gondwanaland. Coal beds are known in South America, Africa, India, Australia, New Zealand, and Antarctica, especially in the upper Paleozoic-lower Mesozoic strata of the Gondwana sequence. Uranium deposits occur in South America, Africa, India, and Australia, mainly as vein deposits, unconformity deposits, sandstone deposits, and fossil placer deposits. The wide distribution of mineral resources across the known pieces of Gondwanaland implies their probable existence within the least known piece—Antarctica. Because of limited rock exposure and hostile environment, a search for mineral resources in Antarctica would be difficult and expensive. Should promising mineral deposits be found, their exploitation would require both large investments and the development of new technology.

INTRODUCTION

Evaluation of the mineral resources potential of Antarctica requires that Antarctica be studied in the context of its central position in Gondwanaland through a long interval of geologic time. This introductory paper, written so that the lay reader can follow, reviews the concept of Gondwanaland (name explained by *Sengor* [1983]), discusses some principles of mineral deposit occurrence and formation, describes the distribution of certain mineral resources across Gondwanaland, and considers the likelihood of mineral resources in Antarctica.

For many decades the permanence of continents was a strongly held tenet among geologists, and only about a century ago did some scientists first argue that continents widely separated today were once joined together. The evidence offered by early advocates of continental displacement was mainly morphologic (similarity of shorelines), stratigraphic (similarity of layered rock successions), and paleontologic (similarity of faunas and floras). Based on his wide field experience in Africa and

South America, the South African geologist *DuToit* [1937] mustered extensive evidence for the existence of the supercontinent Gondwanaland.

Despite these eloquent pleas from some workers in the southern hemisphere most geologists remained very skeptical of continental drift, primarily because of the lack of any suitable mechanism, until about 25 years ago. In the 1960s, several new discoveries and critical observations led to the concept of plate tectonics, and large lateral displacements are a natural and necessary part of this tectonic model. In only a few years the pendulum of opinion about Gondwanaland swung from general disbelief to widespread acceptance.

Through the years, many reconstructions of all or part of Gondwanaland have appeared in the literature, and new refinements will continue to be made. The reassembly shown here (Figure 1), which differs only slightly from that of *DuToit* [1937], is well suited to the purpose of this paper because it preserves the modern shapes of landmasses and the relative positions of mineral deposits. No attempt has been made to adjust for postbreakup

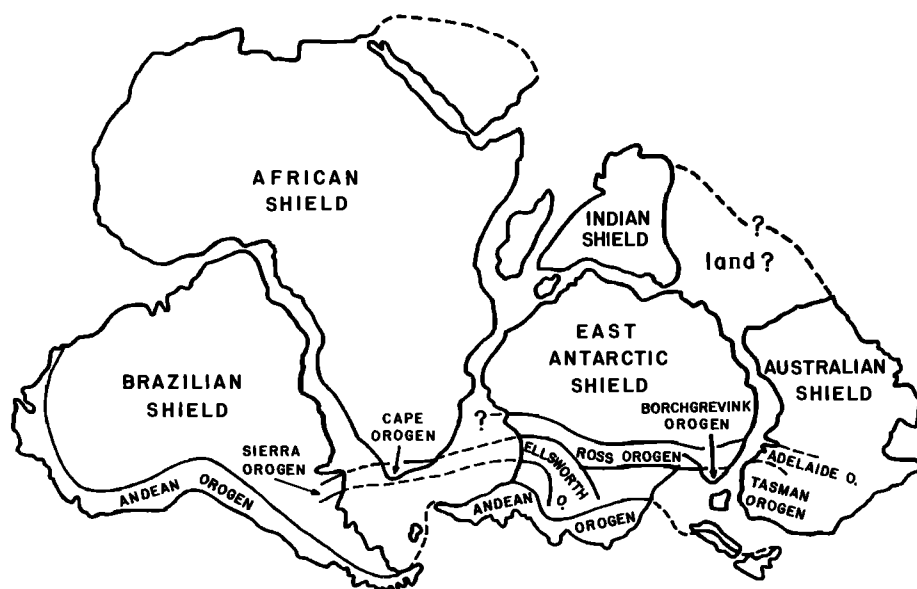


Fig. 1. Reconstruction of Gondwanaland, modified from *Craddock* [1970], based on modern shapes of landmasses. Age of Ross-Adelaide orogen is early Paleozoic; Borchgrevink orogen, middle Paleozoic; Sierra-Cape-Ellsworth orogen, early Mesozoic; and Andean orogen, late Mesozoic/Cenozoic.

tectonic distortions such as bending of fold belts, incipient rifting, or strike-slip faulting, as postulated by *Schmidt and Rowley* [1986] and others.

The central position of Antarctica within Gondwanaland is evident in Figure 1, but as late as 1955 the geology of Antarctica was very poorly known. Most early work was along the coast or on the Antarctic Peninsula, and when the International Geophysical Year (IGY) began in 1957, much of the interior remained unmapped and unvisited. In the years since IGY, geologists from more than 20 nations have carried out a great amount of field work in all major areas of rock exposure, and the broad patterns of Antarctic geology have been established. This wealth of new information strengthens the case for Gondwanaland and improves the accuracy of the reassembly.

Four Phanerozoic orogens have been recognized in Antarctica: the Ross (early Paleozoic), the Borchgrevink (middle Paleozoic), the Ellsworth (early Mesozoic), and the Andean (late Mesozoic/Cenozoic) [*Craddock*, 1972]. These orogens provide important ties with the other Gondwanaland fragments and aid materially in the reconstruction. A Cenozoic volcanic province has also been identified, lying for the most part close to the Pacific border, but it is not shown separately in Figure 1. Because of limited exposures and widespread early Paleozoic resetting of radiometric ages, it is not yet possible to divide the East Antarctic shield into provinces with confidence. The writer has discussed elsewhere the relationship of Antarctica to Gondwanaland

[*Craddock*, 1978] and the evolution and fragmentation of Gondwanaland [*Craddock*, 1979].

In this paper the mineral resources of Gondwanaland are considered in the hope of shedding light on the mineral resource potential of Antarctica. Only the major patterns of selected mineral types are discussed, and the problems posed by individual deposits, however fascinating, are not treated here. Resources must be distinguished from reserves, and *Cameron* [1979] offers useful definitions. Mineral resources are mineral materials actually or potentially available to man. Mineral reserves are mineral resources contained in mineral deposits already found, already explored and sampled sufficiently that their tonnages and grades can be calculated within acceptable limits, and judged to be mineable within the existing framework of society. In most parts of Gondwanaland, sufficient exploration has occurred that both mineral resources and reserves can be identified. In Antarctica, however, although a number of mineral deposits have been found, probably none is known well enough to allow calculations of tonnage and grade; hence no mineral reserves exist at present in Antarctica.

SOME PRINCIPLES OF MINERAL OCCURRENCE AND FORMATION

The location of new mineral deposits is an important and challenging responsibility of exploration geologists, geophysicists, and geochemists. In fulfilling this task the

geoscientist seeks to understand the distribution of related deposits, to classify each deposit according to its main characteristics, and to establish the origin of each deposit. A wide array of geological, geophysical, and geochemical techniques may be employed in the course of this work.

The location and distribution of related mineral deposits are usually controlled by one or more geological factors. Commonly, the deposits will form a mineral belt, a distinctly linear zone, which may coincide with a structural feature such as a fold belt or with a particular rock type such as a greenstone. In some cases the deposits fall on a straight line, and the search for such lineaments may be pursued on air photographs or satellite images. Thus it is generally useful for the exploration geologist to identify mineralized belts or lineaments and to project these trends into areas of unknown or poorly known geology. *Crawford* [1970] shows the value of projecting such trends from continent to continent within Gondwanaland.

Many schemes for the classification of mineral deposits have been proposed, reflecting the many geological factors involved and the various approaches to the problem. Most classifications attempt a subdivision based on genesis, but in many deposits unequivocal evidence for process and conditions is lacking. The details of these classification systems are not important here except to point out that certain processes may not have occurred during late Cenozoic time in Antarctica if it has been glaciated for 20–25 million years. The ice sheet and the cool climate would work against such processes as (1) deep and intense chemical weathering of surface rocks, (2) concentration of heavy minerals into placer deposits by streams, and (3) precipitation of evaporite minerals from shallow seas, although the cold water temperature must be partly counteracted by the low relative humidity.

Until recently, geologists had no generally satisfactory model for explaining mineral belts, anymore than they did for orogenic belts or metamorphic belts. Typically, the geologist would describe an individual mineral deposit, seek to establish the process and the environmental conditions, and then classify the deposit in one of the schemes. But little could be said about the ultimate cause for the deposit or the belt. Today the plate tectonics model offers a reasonable explanation for many mineral deposits by relating them to processes occurring at convergent, divergent, or transform plate boundaries [*Wright*, 1977].

The mineral resources of Gondwanaland are widespread and diverse (Figure 2); only those judged to be most significant have been plotted on the map. Antarctica has been left blank here for effect, even though some mineral occurrences are now known there; some of them are addressed in other papers in this volume. The 16 mineral types selected for plotting are mainly

materials used in great quantities or materials with high value per weight unit. On the map, emphasis is placed on large deposits and on deposits close to Antarctica or to another divergent continental margin. A brief description of the most important characteristics of each of these mineral types follows.

METALS AND PRECIOUS STONES

The mineral resources treated in this section are divided into (1) major metals, used in large quantities, (2) minor metals, important but used in smaller quantities, (3) precious metals, rare and very expensive, and (4) precious stones.

Major Metals

Although other types of deposits are locally important, most reserves of iron ore are found in Precambrian banded iron formations of sedimentary origin. Such formations are widely distributed in the Precambrian shields of both the southern and northern hemispheres; most of them are early Proterozoic in age (~2 billion years old). Interlayered bands of silica are commonly present, and the iron minerals may be oxides, carbonates, silicates, or sulfides. The Hamersley iron range in northwestern Australia has enormous reserves, and other major deposits occur in northern South America.

Copper deposits are scattered and varied, but two districts bear special mention. The Central African Copperbelt is one of the most important in the world. The copper occurs in stratiform deposits within deformed upper Precambrian sedimentary beds; the deformation may have occurred during early Paleozoic times, as in the Ross orogen. Another belt of rich copper deposits, the porphyry coppers, extends northward from central Chile along the Andean chain of South America. These deposits occur in felsic intrusive bodies, typically granodiorite, which have undergone fracturing and alteration. These plutons are probably related to Cretaceous-Cenozoic subduction along the west coast of South America. Chuquibambilla, Chile, is the largest copper deposit in the world [*Dixon*, 1979].

Lead and zinc commonly occur together and tend to form small deposits of vein or replacement type. Any rock type may serve as the host, but many deposits exist as sulfide minerals within sedimentary layers. Silver is also present in many of these deposits.

Aluminum has not been plotted on the map, because bauxite forms best in warm, humid settings. Bauxite is not likely to occur in Antarctica owing to the hostile climate and the probability of removal by ice sheet erosion.

Minor Metals

Nickel occurs in mafic to ultramafic bodies, and in the southern hemisphere the individual deposits tend to be

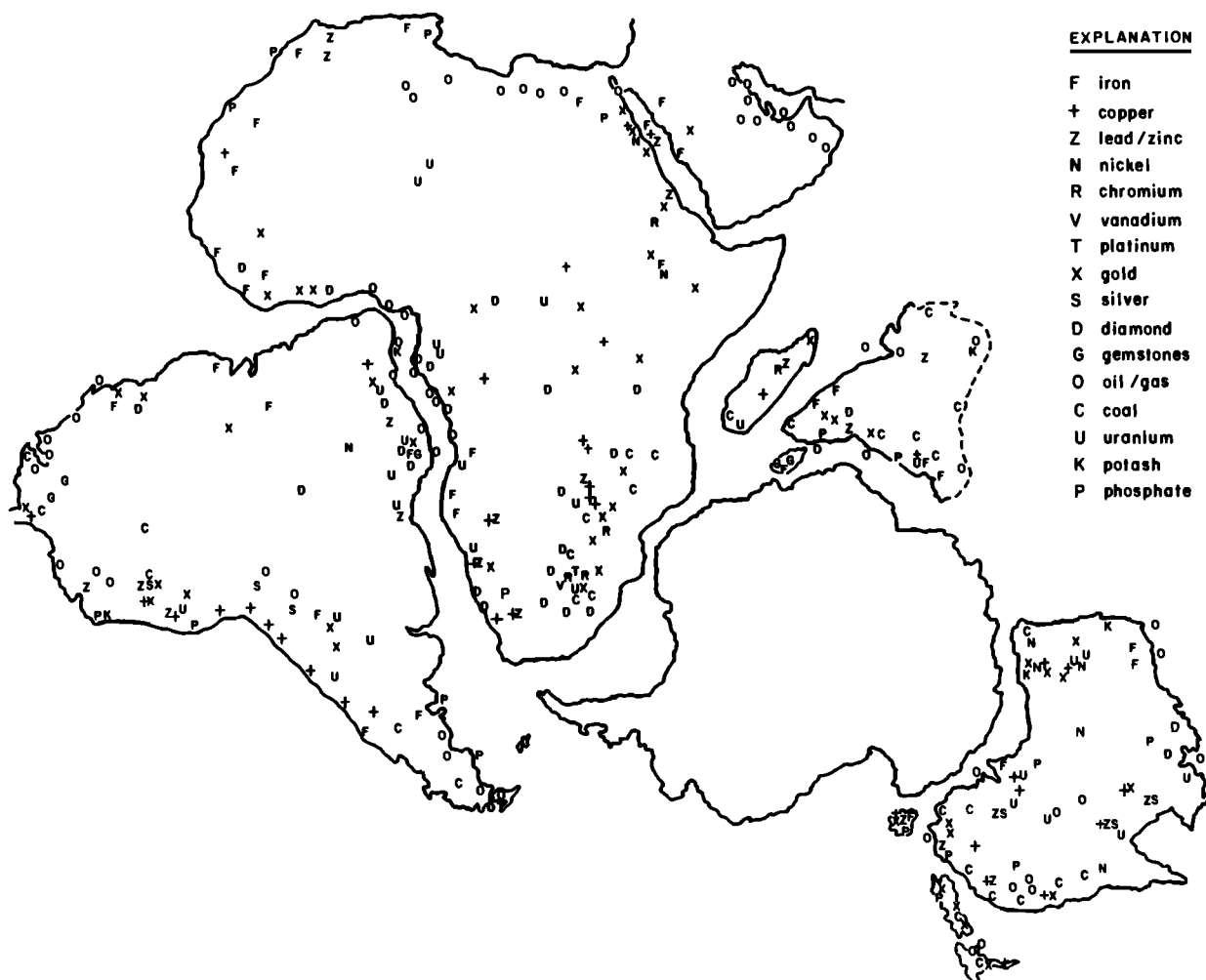


Fig. 2. Selected mineral deposits of Gondwanaland, exclusive of Antarctica. Compiled from many sources, including Deffeyes and MacGregor [1980], Derry [1980], Dixon [1979], Fletcher [1980], Fletcher and Soeparjadi [1984], Herath [1975], Lee [1980], Lombard [1968], Petersen [1979], Ponte et al. [1980], and Rachwal and DeSefano [1980].

small in terms of world reserves. Recently, new mines have been established to recover nickel from deeply weathered surficial rock in tropical areas.

Chromium occurs mainly as the mineral chromite within mafic to ultramafic intrusions. Chromium is a strategic mineral, and southern Africa is a major world supplier. Large reserves occur in the Bushveld Complex of South Africa and the Great Dyke of Zimbabwe.

Vanadium is a trace element of great importance in steel making. It is found in a variety of geologic settings and is generally produced along with some other element, commonly iron. The USSR and South Africa are the two leading producers of vanadium.

Precious Metals

Gold occurs in many types of deposits across Gondwanaland, but especially in sedimentary placer deposits or in association with felsic igneous intrusions. About half of world reserves are in South Africa, especially in the Witwatersrand district, but significant deposits also occur in South America, Malagasy, India, Australia, and New Zealand.

Silver is commonly found in vein or replacement deposits where it tends to occur with either lead or gold. It may exist as free silver or in a variety of combined states, mainly sulfide minerals. The most productive

belt of silver deposits in Gondwanaland lies in the central Andes Mountains in South America.

Platinum is a rare but important element that occurs in mafic to ultramafic igneous bodies. Most of the world reserve is found in a thin zone within the Bushveld Complex of South Africa. South Africa, USSR, and Canada account for nearly all the world production.

Precious Stones

Diamonds have been found at many localities across Gondwanaland, mainly in the form of placer deposits. The original source of such diamonds is generally unknown. However, diamonds occur in place in many kimberlite pipes in southern Africa.

Gondwanaland contains many important gemstone deposits; *Saul* [1970] reports 13 districts that define a belt across the supercontinent, but he does not provide a map. Brazil and Sri Lanka have the most important deposits; the gemstones occur mainly within pegmatite veins or in placer deposits.

MINERAL FUELS

The mineral fuels treated here are divided into (1) petroleum and natural gas, (2) coal, and (3) uranium.

Petroleum and Natural Gas

With the exception of the northern margins of South America and Africa-Arabia and the western margin of Africa, the hydrocarbon production and reserves of Gondwanaland are modest. In the past, exploration has been limited by the prevalence of Precambrian rocks at the surface and the remoteness of much of the area from principal world markets. In recent years, however, the exploratory pace has quickened, and some interesting discoveries have been made. Australia, for example, had almost no oil production as late as 1960, but in 1987 it had significant daily production (Table 1) and 157 productive fields.

Along the convergent margins at the outer edges of Gondwanaland, hydrocarbon production has existed for decades in the Persian Gulf area and along the Andean chain and foreland in South America. Important re-

serves have now been established in northern Africa, and small discoveries have been made recently in New Zealand. It is noteworthy that West Antarctica appears to have been a convergent margin through much of Phanerozoic time.

But the most interesting new discoveries have been made along the divergent margins, in some cases not many kilometers from outcrops of Precambrian rocks. Notice in particular the fields along the Atlantic margins of South America and Africa, the southeastern margin of Australia, and the new discoveries off the east coast of India (Figure 2). Production in these areas is from Cretaceous or Tertiary reservoirs, beds deposited along the continental margins after the fragmentation of Gondwanaland was under way. Much of the margin of East Antarctica is likely to be generally similar to the opposed coasts now far away.

Coal

Important deposits of coal are found in the Gondwana sequence (Devonian-Jurassic), mainly in Carboniferous and Permian beds, in many of the fragments of Gondwanaland. Interestingly, the coal beds are usually closely related stratigraphically to glacial beds. The coal beds of eastern Australia appear to have a southward continuation in the Transantarctic Mountains, and one of the coal basins of eastern India may have originally extended into the Lambert Glacier area along the coast of East Antarctica.

Uranium

Uranium-bearing minerals occur principally in veins, in sedimentary beds (especially coarse-grained clastic rocks), and in igneous plutons. In many cases the relative age and origin of the uranium mineral in the sedimentary bed are not clear; some are considered to be placer deposits. Uranium deposits range in age from Archean to Tertiary. Uranium occurs with gold in the Witwatersrand district, South Africa, and many uranium deposits occur elsewhere in Gondwanaland.

OTHER MINERAL RESOURCES

Two mineral resources that are important in the manufacture of fertilizers, potash and phosphate, are also shown in Figure 2. Although many deposits are small, these substances are widely distributed and represent an important asset for the local agricultural economy [*Sheldon*, 1982]. The deposits along the coast of northwest Africa hold very large reserves of phosphate.

Gondwanaland holds other mineral resources which are not portrayed in Figure 2. Many pegmatites yield tin and related elements as well as feldspar, mica, and other

TABLE 1. Oil Production in 1987 From Some Gondwanaland Areas

Area	Oil Production, barrels/day
Argentina	417,000
Colombia	385,249
Venezuela	1,796,912
Australia	544,000
Central and southern Africa	2,100,000

Source: *Bulletin of American Association of Petroleum Geologists* [1988].

minerals. Other deposits include such materials as asbestos, bauxite, graphite, and quartz crystal.

The great mineral wealth of southern Africa deserves special emphasis because of its proximity to Antarctica in the Gondwanaland reassembly. The two nations of South Africa and Zimbabwe contain one of the most heavily mineralized Precambrian terranes in the world. This region includes a high percentage of the known world reserves of several important mineral commodities. This province could extend into coastal East Antarctica.

ANTARCTIC MINERAL RESOURCE POTENTIAL

The evidence supporting the existence of Gondwanaland well into Mesozoic time has become very strong, and the central position of Antarctica seems well established. Exploration of the inhabited parts of Gondwanaland has revealed a large and diverse population of mineral deposits, some of great value and some of great strategic importance. It is highly improbable that Antarctica is the only continent on Earth wholly void of significant mineral deposits. Antarctica is unique among the continents, of course, in having more than 95% of its total area masked by an ice sheet.

Certain Phanerozoic fold belts in South America, Africa, and Australia appear to have continuations in Antarctica, and related belts of mineral deposits may behave in the same way. Some copper-bearing plutons on the Antarctic Peninsula resemble the Andean porphyry copper bodies, although the Antarctic plutons tend to be less altered than the Andean ones. The Dufek intrusion, a layered gabbro complex near the African end of the Transantarctic Mountains, bears resemblance to the Bushveld Complex in South Africa. Recent geophysical surveys [Behrendt *et al.*, 1980] suggest that the two complexes are comparable in areal extent, although they are quite different in age.

Shows of hydrocarbons were encountered in 1973 during Deep Sea Drilling Project Leg 28 while drilling on the continental shelf in the Ross Sea area. Little is yet known about the continental margins of Antarctica, especially with regard to the thickness and composition of the sedimentary successions from place to place. Nevertheless, the discovery of hydrocarbons along the Atlantic coasts of South America and Africa, the east coast of India, and the south coast of Australia underscores the possibility of similar accumulations along the coast of Antarctica.

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TOWARD A QUANTITATIVE MINERAL RESOURCE ASSESSMENT OF ANTARCTICA FROM A GONDWANA PERSPECTIVE

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Since a new, detailed geological map and data base (including geological and partially tectonic and geochronological data) of Gondwana have been installed on the Intergraph computer system, our Gondwana research has extended into the field of geochemistry, with particular emphasis on the distribution of some transition elements (e.g., Au, Cu, Zn) within the mineral deposits across Gondwana. We are in the process of constructing quantitative resource maps (metal-anomaly maps) of Gondwana together with an accompanying metallogenic data base. The data base comprises alphanumeric minerals data and is linked to the existing geological data base through the digitized Gondwana map. Because the Intergraph system offers the capability of rapidly linking graphics and nongraphics data bases, interactive enquiries and manipulations of the nongraphics data can be made from the digitized map. By pursuing a relationship between metallogenesis and plate tectonics we propose to formulate an assessment of Antarctica's mineral endowment within the framework of this Gondwana Earth science data base and mineral economics theory (i.e., wealth models). Such an assessment would be more accurate than the "sweeping" estimate which proposes a mineral endowment of Antarctica beneath its ice cover similar to other equal-sized land masses.

INTRODUCTION

The concept of Gondwanaland (or Gondwana, as is now accepted as the more correct term: Gondwanaland means land of (the land of) the Gonds) as a single land mass or supercontinent was first introduced in 1883 by the Austrian geologist Eduard Suess. It included the regions of India, Malagasy, Africa, and South America. Thirty years later, Alfred Wegener extended this region to include Australia and Antarctica (Figure 1). Today, the idea of the supercontinent, known to have existed at least 150 million years ago, is accepted as a fundamental fact of the Earth science community and has recently become the focus of renewed and vigorous scientific investigation. For example, several computer programs are now available which allow various rapid reconstructions of Gondwana to be compiled, based on geophysical data (i.e., from the Scotese group in Houston, the Ziegler group in Chicago, and the Smith group in Cambridge, United Kingdom). Also, a 1:10 million geological map of Gondwana has recently been published both in the form of a hard copy wall map and as a digital data base [de Wit *et al.*, 1988].

Experience and hindsight gained from the production of the Gondwana geological map and its digital data base (a 9-year project) are presently being exploited to extend this research into the fields of geochemistry (with particular emphasis on mineral deposits) and geophysics

(gravity and magnetics) of the Gondwana lithosphere: G³, Gondwana Geochemistry and Geophysics.

Current research into the geochemistry of the Gondwana lithosphere visualizes the production of transition (and other) element distribution maps (namely, metal-anomaly maps: contour maps of Pb, Cu, Zn, Au, U, etc.), to be integrated with the existing data of the geological map of Gondwana.

The objectives are as follows: (1) to construct quantitative resource maps, in contrast to the qualitative metallogenic maps hitherto available; (2) to establish a metallogenic data base of Gondwana which will add to the present geological data base; (3) to facilitate quantitative assessments of the Earth's resources of specific, largely unmapped areas, in particular, those covered by desert (north and south central Africa), dense forests (Brazil and Zaire), and ice (Antarctica); and (4) to investigate geochemical processes within the Gondwana crust from these "tracer maps" with implications for crustal recycling, and the tectonic evolution of the continental lithosphere.

METALLOGENESIS AND MINERAL POTENTIAL OF ANTARCTICA

When viewed in a Gondwana framework, there is no reason to doubt that Antarctica's ice sheet is underlain by large mineral deposits. Every other continent is host to such deposits, and the basic geological architecture of

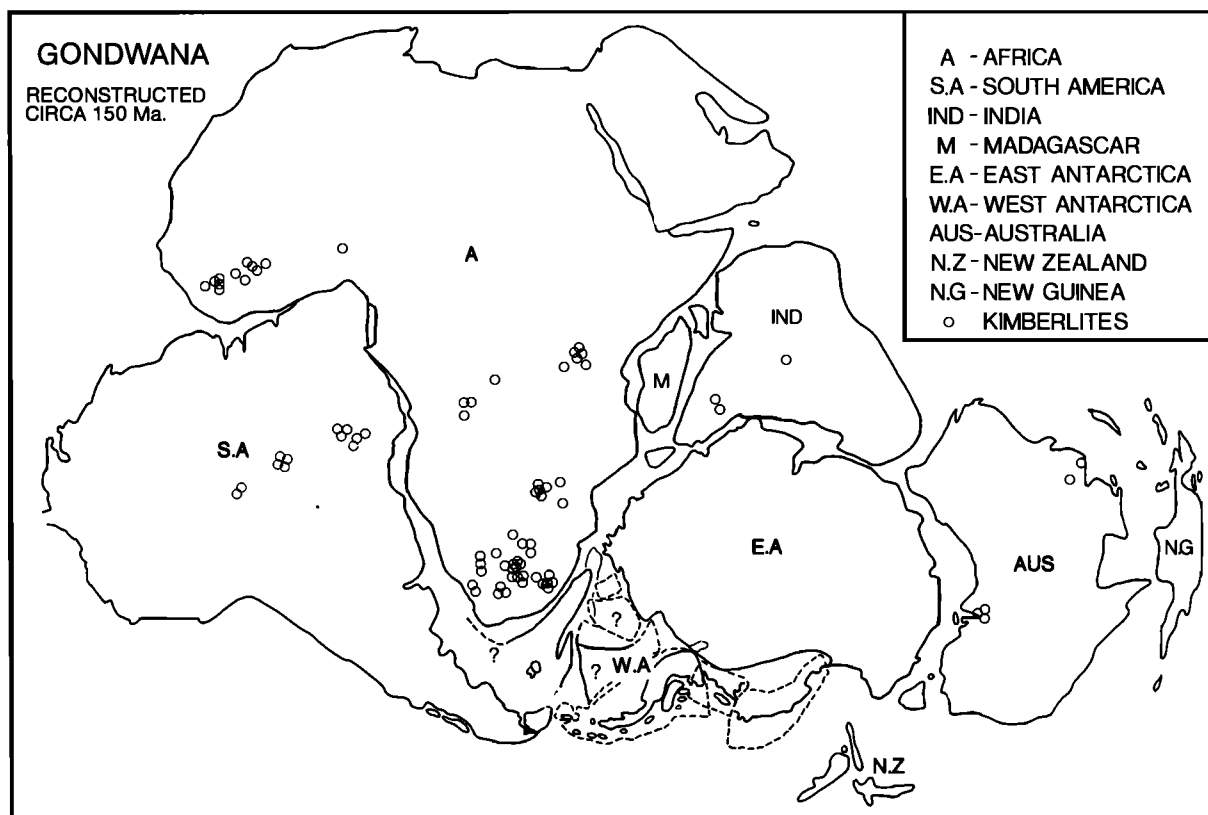


Fig. 1. Reconstruction of Gondwana at circa 150 Ma, showing the central position of Antarctica in this framework. (Equal area projection, after *de Wit et al.* [1988].) Also shown is the distribution of most known kimberlites (taken from *de Wit et al.* [1988]). Intuitively, from this spatial distribution, kimberlites can be expected to have intruded the Antarctic crust. However, kimberlites are only diamond bearing in specific environments. Thus geological factors are also necessary for modifying any statistical estimate of the diamond resource potential of Antarctica. (See text for further explanation.)

the Antarctic continent is not dissimilar [*de Wit et al.*, 1988]. But while Antarctica is still largely inaccessible to current exploration methods, is it possible to construct a more accurate resource inventory of the continent than the "sweeping" estimate which proposes a mineral wealth for Antarctica which is similar to other equal-sized land masses?

In our ongoing work toward establishing a more detailed mineral resource assessment of Antarctica, two key words from the list of objectives are "metallogenic" and "quantitative."

Metallogeny, as the name implies, is the study of the genesis of mineral deposits with emphasis on their relationship in space and time to regional geological features of the Earth's crust. In this regard, two additional terms are defined: a metallogenic province and a metallogenic epoch [*Bilibin*, 1968]. A metallogenic province is a geologically defined area, characterized by a particular group of mineral deposits (e.g., the tin prov-

ince related to the Nigerian aluminous intrusions). It may have experienced more than one episode of mineralization within it, and therefore the notion of time is also an important dimension. A metallogenic epoch describes the unit of geologic time favorable for the deposition of an assemblage of ores and may describe a period of mineralization for more than one province.

Historically, the concept of metallogenic provinces was developed from observations of the distribution of mineral deposits across the surface of the Earth; mineral deposits are distributed rather irregularly. Copper deposits, for example, may be abundant in some regions, while lead, zinc, and tin are predominant in others [*Sillitoe*, 1976; *Redwood*, 1987]. A catalog of the various metallogenic provinces throughout the Earth's surface provides useful information both for the explorationist and the theoretician who would attempt to understand the causes of and conditions for the formation of ores within a particular province.

To date, none of the many avenues of investigation have been able to explain the occurrences of metallogenic provinces and epochs adequately. Rather, it is clear that metallogenesis is one of a range of complex geologic processes involved in crustal evolution, including sedimentation, tectonism, magmatism, metamorphism, and their interactions.

The viewing of mineral deposits in a plate tectonic framework has vastly improved the general understanding of metallogenesis [e.g., *Mitchell and Garson*, 1981; *Sawkins*, 1984]. Plate interactions generate various types of lithological assemblages and therefore have been used successfully to interpret different geological terrains. The exploration of mineral deposits which are concentrated in particular lithological sequences can be aided, then, by the study of their tectonic setting.

Further, each tectonic setting may exert a control on the type of mineralization found within it as well as the deformation and the preservation potential of the mineral deposits themselves. The following arguments by *Mitchell and Garson* [1981] justify such a relationship.

1. The various types of magmatism, each of which is related to a particular mineral assemblage, are characteristic of one or more tectonic settings.

2. The nature of sedimentary successions is at least in part related to the tectonic environment in which the sediments are formed.

3. The nature and degree of metamorphism are often dependent on the tectonic setting.

4. The geothermal gradient is affected by the tectonic environment.

5. Faults, which can control the circulation of mineralizing fluids, are considered to be a type of tectonic setting.

While an investigation of present-day plate boundaries in relation to metallogenesis may yield important mineral exploration tools, the interpretation of many, and in particular ancient, geological terrains in light of the modern view of plate tectonics should be tackled cautiously. The evolution of the ancient crust may not have involved the same plate tectonic processes, and ancient crust may also be severely altered from its original form. Because time is an important dimension in the metallogenic process, a description of mineral deposits in relation to a particular tectonic setting must also include a reference to the time of formation. *Barton* [1983] has suggested, also, that mineral deposits can reveal more about (plate) tectonics or geological environments, in general, than vice versa.

A simple example is that of certain economic, diamondiferous deposits. Figure 1 illustrates the distribution of some kimberlites (the main magmatic, diamond host) in the Gondwana lithosphere. The ages of these kimberlites range between circa 80 and 2000 million years. Kimberlites of this age range may occur in any province (e.g., the South African province; Figure 1).

However, only where kimberlites intrude old, well-preserved host rocks (i.e., cratonic rocks >2500 million years old) are they diamondiferous. Clearly, as a corollary, looking for such deposits in Antarctica, geological and geochronological background knowledge of the host rock to the kimberlites is essential and needs to be integrated with a purely spatial and/or tectonic approach.

As far as the interpretation of old (Archean) terrains is concerned, some of the ancient rocks can be described as having formed in environments similar to various modern settings, with some success. It is thought, therefore, that certain similar lithological assemblages have been generated repeatedly throughout much of Earth's history [*Windley*, 1984]. However, evolutionary trends of the crust over time may reflect changing conditions in global heat flow, crustal segregation from the mantle, the chemical nature of the atmosphere and hydrosphere, and a progressive modification of the composition of the crust.

These variations must have effected the partitioning of elements (such as those needed to form economic mineral deposits) between the mantle and the crust with geologic time and, hence, the rate of formation of certain types of deposits. Mineral deposits of the platinum group elements (PGE), diamonds, gold, chromium, nickel, vanadium, and manganese, for example, are disproportionately endowed in Archean cratons, relative to the total resources of the world, but are also not homogeneously distributed among these regions; nor are they necessarily of Archean age. The Archean rock records, however, demonstrate that these cratonic areas were subject to similar histories. Additional geological factors, therefore, need to be called upon to compare these "similar" cratons, and factors such as different levels of uplift and erosion of Archean rocks have been used to explain the heterogeneous distribution of mineral deposits among cratons [*de Wit*, 1985].

Other problems encountered in formulating a mineral inventory of specific areas (e.g., Antarctica) include crustal recycling (a currently contentious issue), thermal or mechanical distortion associated with later orogenies, and sedimentation which may blanket mineral provinces with a thick succession of sediments.

Even if plate tectonics was (strictly) uniform over Earth's history, other critical factors governing the formation of metallogenic provinces are important for the compilation of a mineral inventory.

Concerning the mineral potential of Antarctica, although many mineral occurrences (or indeed resources, such as coal and iron) have been reported, no mineral reserves have been shown to exist, to date (*de Wit* [1985] and various authors in this volume). This is due to the lack of solid rock exposure and, more accurately, as a result of Antarctica's inaccessibility and related exploration logistic problems. As far as solid rock expo-

sure is concerned, too, the lack of indicators of mineral deposits on surface is no longer sufficient to negate the existence of mineral deposits at depth.

As was already noted, the southern hemisphere continents represented one land mass, Gondwana, some 150 million years ago in which Antarctica occupied a central position (Figure 1). In fact, it is known that Gondwana had, at that time, been in existence for at least 500 million years. Disruption of Gondwana, widely separating continental fragments from east Antarctica, occurred successively, starting with Africa and South America (150–160 Ma), India (120 Ma), New Zealand (70–80 Ma), and Australia (50–60 Ma). Therefore any mineral deposits which formed between 700 and 150 million years ago should be studied within a framework of the metallogenic provinces of Gondwana. Configuration of Gondwana prior to 700 million years ago, however, is not known, and extrapolations of ore deposits older than this age, therefore, must be attempted with great care and in conjunction with other geological and paleomagnetic constraints.

GO-GEOID: A GONDWANA GEOSCIENTIFIC DATA BASE

As is apparent from the above overview, any attempt at quantifying a mineral inventory of Antarctica must be approached as an exercise in multidisciplinary analysis [cf. *Harris*, 1984]. To date, the only form of mineral assessment of any particular area is in the pattern of a metallogenic map.

A relatively good metallogenic map is one which shows the different types of metal deposits which are formed within a narrow time range (usually less than 10–20 million years). Obviously, a clear understanding of metallogenesis and tectonic environments is required to interpret the results of such maps. Present metallogenic maps, however, are very qualitative, and in part subjective, and therefore are of limited use to both researchers and for the mining and exploration communities. Furthermore, each mineral deposit is represented as a colored symbol, the meaning of which needs to be systematically and tediously decoded. These data are not generally available in digital form and cannot therefore be manipulated or modeled for useful interpretation. Quantitative interpretation and extrapolation would only be possible if these and other data were stored in digital form.

Essential, then, in achieving our objective for a quantitative assessment of mineral resources of Gondwana has been, and is, the design and implementation of a comprehensive Gondwana-Geoscientific Indexing Data Base (GO-GEOID). The geology, geochronology (partially), and tectonic data are at present available in digital form, having been compiled from the geological map, while the mineral information is being added. By

interrelating these multidisciplinary data across Gondwana, a great wealth of information is made available for various graphical, statistical, and other modeling or general inquiry purposes.

These different fields of information, then, are interrelated through the data base and also linked together via a graphics design file. This design lends itself to the easy manipulation of data, both from the graphics and from the nongraphics files. For example, it will be possible to contour the distribution of a selected mineral or element within a chosen geographical and/or geological (tectonic) area.

GO-GEOID is designed not only for the current research requirements, but with a flexibility for future applications and additions. For example, the addition of gravity and aeromagnetic data of Gondwana is at present also being investigated. Also, the design of GO-GEOID (i.e., partitioned into the different disciplines) allows for easy modification and portability of these data between different hardware and data base management systems.

With reference to each Gondwana mineral deposit, the following information is stored: (1) mineral identity; (2) location in geographic coordinates (or other identified coordinate system); (3) grades (of different elements) and tonnages (or estimates) thereof; (4) age and dating techniques (plus any isotopic information); (5) nature of mineralization (e.g., vein deposit); (6) host rock or surrounding country rock; (7) age of host rock and dating technique used; (8) mineral association; (9) tectonic setting, where apparent; and (10) sources of information (reference).

Table 1 lists the initial selection of elements chosen for this study. The elements extend across the geochemical classes (lithophile, chalcophile, and siderophile), which is a prerequisite to test the distribution of elements in the Gondwana crust with regard to their time-integrated, geochemical behavior. This chosen group of elements, therefore, represents a cross section of chemical behavioral patterns of elements within the Earth. As can be seen from the table, most of the elements are transition elements (the distinguishing electron occupying a *d* subshell) with reference to their electronic configuration. The elements have a range of abundances in the Earth [after *Ganapathy and Anders*, 1974] from 18 ng/g (for U) to 2.04% (for Ni).

From this collection of elements, it is hoped both that various large-scale geochemical differentiation processes can be tested and that the relationship between mineral deposits, tectonic settings, and time may be developed further. Specially for Antarctica, it is anticipated that mineral resource inventory will be established on the basis of combined Gondwana geological, geochemical, geochronological, mineral, and tectonic information, all available in digital form. The procedure is described briefly below.

TABLE 1. Elements Selected for the Mineral Resources Assessment of Antarctica

Symbol	Element/Group	Geochemical Association*	Comments Relating to Ore Deposition
U	uranium	lith	incompatible/radioactive
Th	thorium	lith	incompatible/radioactive
REE	rare Earths	lith	incompatible
Ti	titanium	lith	substitutes for Fe and
Cr	chromium	lith	Mg in magmatic spinels
Cu	copper	chal	important base metal in
Zn	zinc	chal	remobilized sulphide/
Pb	lead	chal/sid	sulphate minerals
Ba	barium	lith/chal	
PGE	platinum group	sid/chal	enriched in Archaean
Au	gold	sid/chal	rocks
W	tungsten	sid	incompatible; separates
Mo	molybdenum	sid/chal	into late phase
Sn	tin	sid/chal	residual minerals
Sb	antimony	chal	
Ni	nickel	chal/sid	important metal in
Cu	copper	chal	primary magmatic
Sb	antimony	chal	sulphide minerals

*Abbreviations: lith, lithophile; chal, chalcophile; and sid, siderophile.

COMPUTER GRAPHICS, METAL-ANOMALY MAPS, AND A MINERAL RESOURCE ASSESSMENT OF ANTARCTICA

The concept of GO-GEOID has already been discussed in brief. For interpretation and extrapolation purposes, these multidisciplinary data must be linked to the geographical information of Gondwana.

At present, our project is using the Intergraph system: a system which can integrate computer graphic information with nongraphic data bases. The Intergraph system functions as a 32-bit machine, supported by VAX- and MicroVAX-based hardware, and allows the production of maps with supporting nongraphic information. Further, the nongraphic data base can be partitioned in such a way as to be multidisciplinary but linked together via a hierarchical order or network to the geographic base map.

Establishment of a graphics data base (or design file, as it is termed) utilizes the facility of the Intergraph system to maintain any level of graphic accuracy with 4 billion addressable points per axis. The system can also handle very large data bases envisioned for the multidisciplinary Gondwana project.

The geographic information is stored in vector form but allows processing of both polygonal and grid data. Thematic inventories can be separated and stored on up to 63 levels, the system allowing access to any level or combination of levels. The Interactive Graphics Design Software (GDS) provides a complete editing repertoire through which map elements can be moved, rotated, copied, etc. Already the geological map of Gondwana

exists on the Intergraph system as design file, using all of the available levels for various boundaries and patterning.

The design file is then given "intelligence" by the process of linking the graphics to a nongraphic data base. The Intergraph's Data Management and Retrieval System (DMRS) supports either hierarchical or network data base structures for the storing of textual data, related to the graphics. The connection which is established between the graphics and the nongraphics data bases allows the operator concurrent access to data describing any map element for which a linkage exists.

Management of large data bases can be achieved through an index map, which may, for example, represent the boundaries of smaller map sheets. Subsets of the complete map may be extracted for processing and then posted back into the master data base maintaining data base integrity.

In the context of metallogenic maps, then, user commands can select out specific mineral occurrences from a defined area of the design file. If gold is chosen, for example, the data base is processed and all the gold deposits in a defined area (e.g., close to a specific major fault) are highlighted on the graphics screen. In this way, any attribute can be searched from the graphics.

As an example, a dummy nongraphic data base of the mineral deposits of Bolivia (a small area within Gondwana) was linked to a digitized graphic design file of South America, given in Figures 2 and 3. The data base comprised the following attributes: mineral identity number, geological polygon number, mineral associa-

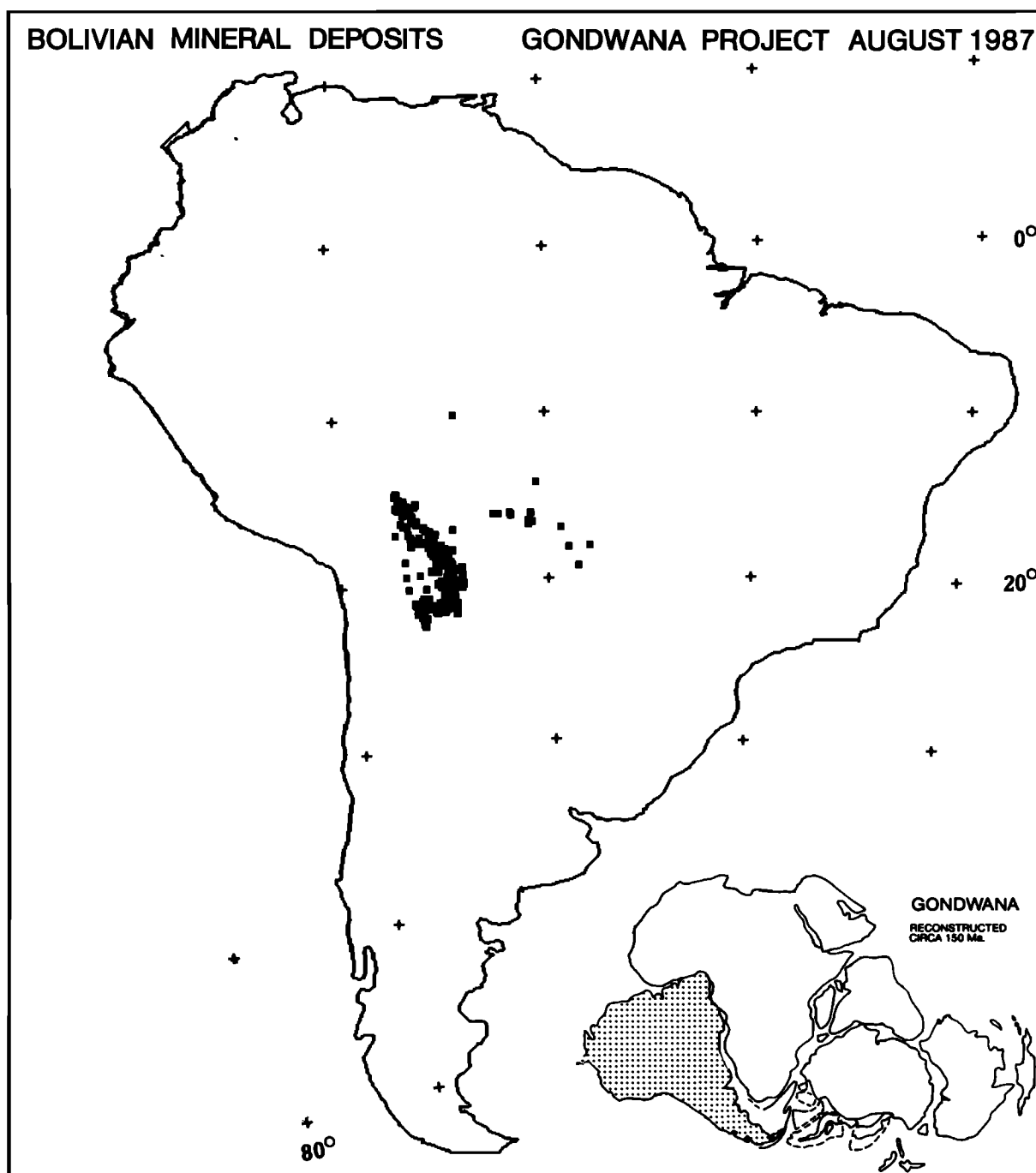


Fig. 2. An example of a dummy, nongraphic data base, linked to the occurrences of mineral deposits in Bolivia (within the South American section of Gondwana), the positions of which were taken from the Metallogenic Map of South America [Martin F, 1983]. These deposits are shown positioned on a digitized outline graphic file of South America. From the GO-GEOID data base, they can easily be rotated back into their Gondwana coordinates.

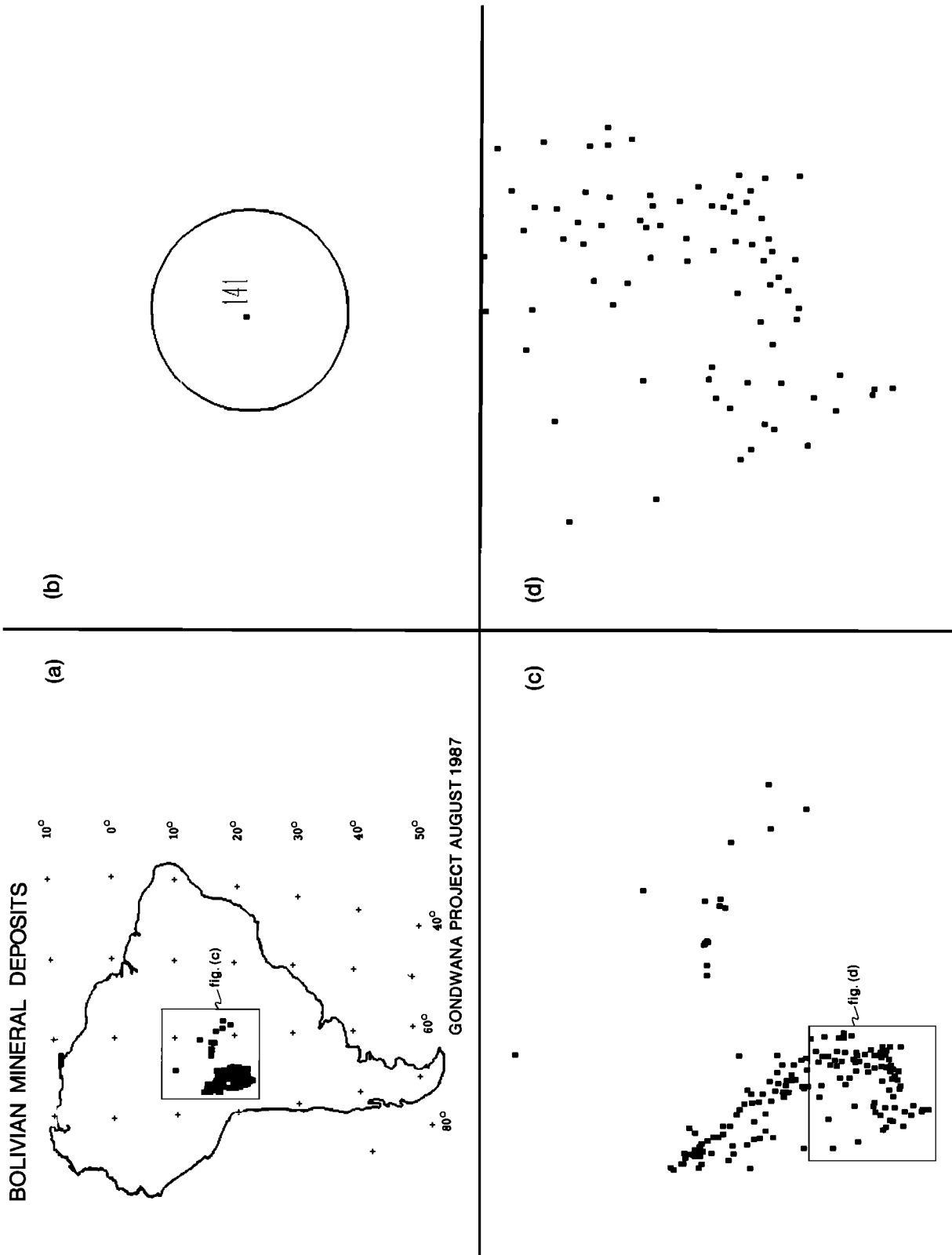


Fig. 3. An example of a graphics design file: the occurrences of mineral deposits in Bolivia within the South American outline, viewed simultaneously on the computer screen at different scales. The largest scale (Figure 3a) shows the entire map, while the smallest scale (Figure 3b) shows an individual deposit occurrence. Figures 3c and 3d are in between these two extremes. The Intergraph system allows editing at any preferred scale, the changes of which are automatically duplicated throughout the other sections.

tion, longitude, latitude, age, type of mineralization, host environment, etc. This data base may contain any number of descriptors and, for the Gondwana project in particular, would also contain values of grade and tonnage for each mineral deposit/occurrence. Figures 2 and 3 show various views of this design file. As described above, a user command was compiled to select out any chosen mineral from the data base. In a similar way, it is the intention to quantify each point or mineral deposit on the Gondwana map with respect to one or more trace elements by the integration of tonnages and grades and implement a contouring scheme to generate quantitative metal-anomaly maps.

We thus envisage that the end product will be a series of Gondwana metal-anomaly maps for specific elements (e.g., gold, platinum, copper, cobalt, etc.), as part of a General Gondwana Earth Science Atlas. On these maps, Antarctica will remain effectively blank. However, by integrating the contours of specific elements of the surrounding continents with the known geological (and potential geophysical data) and mineral deposits data, a quantitative assessment of the resource potential of Antarctica can be made in a space-probability framework.

It is our intention, though, that this resource assessment of Antarctica not be restricted to purely geological and related factors, but include reference to economic and, in particular, resource availability constraints. This may be achieved, for example, by employing occurrence and wealth models of Allais [1957], Slichter [1960], Agterberg *et al.* [1972], and Harris [1984]. In this way, an appraisal of the economic merits of exploration/exploitation programs of large subareas of Antarctica will be produced, such that the outcome can be stated in terms of associated risks, costs, and returns. It will allow for a more accurate mineral accountancy for Antarctica as a whole, upon which more reliable socio-economic and political decision-making can then be based.

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THE DUFEEK INTRUSION OF ANTARCTICA

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The mostly ice-covered, stratiform mafic Dufek intrusion of the northern Pensacola Mountains occupies an area of more than 50,000 km² and has an interpreted thickness of 8–9 km. It is thus one of the world's largest igneous bodies of this type. It has many petrologic similarities with resource-rich intrusions such as the Bushveld Complex (South Africa) and the Stillwater Complex (Montana), but its potential for resources is poorly known. The occurrence in the Dufek intrusion of magmatic ore deposits similar to those of other layered mafic intrusions seems likely. Among possible resources, platinum group elements (PGE) would have greatest economic feasibility for exploitation. The Dufek intrusion is of Jurassic age and coeval with Ferrar magmatism of the Transantarctic Mountains. It was emplaced within a multiple-deformed mobile belt of Triassic and older age adjoining the craton of East Antarctica. Cumulates of earliest origin, presumably in part ultramafic, and those of a 2- to 3-km-thick intermediate interval are not exposed. Mafic cumulates of nearly 2-km-thick exposed sections in Dufek Massif and stratigraphically higher in the Forrester Range show chemical and mineralogic differentiation trends of Fe enrichment comparable to those of other major stratiform intrusions. Sulfide minerals are markedly more abundant in the higher part of the intrusion, where highest PGE abundances are found. However, a possible comparison with the Bushveld's PGE-rich Merensky Reef suggests greatest resource potential in the Dufek's concealed basal section, which requires drilling for evaluation.

INTRODUCTION

Layered Intrusions and PGE Resources

Layered mafic and ultramafic igneous intrusions commonly contain a variety of economic resources, particularly chromium and platinum group elements (PGE) that are concentrated in early mafic and ultramafic cumulate units of lower stratigraphic sections [Wilson, 1969]. The most important PGE concentrations occur at well-defined stratigraphic horizons in the intrusions [Campbell *et al.*, 1983; Hulbert *et al.*, 1988]. The Bushveld Complex of South Africa with its Pt-rich Merensky Reef is the world's largest repository of PGE and many other resources [Willemse, 1969]. Montana's Stillwater Complex [Hess, 1960], a layered mafic-ultramafic intrusion much smaller than the Bushveld Complex (see Table 1 note), also contains significant PGE resources [Naldrett, 1981]. PGE production was recently begun in the Stillwater Complex, from its J-M Reef, which is of the Merensky type [Sutphin and Page, 1986]. This report on the Dufek intrusion of Antarctica (Figure 1) emphasizes PGE resources because they would be the most likely for economic utility [Ford, 1983b].

At present, the world's PGE supply is greatly dominated by mines of South Africa and the Soviet Union, which along with smaller production in four other countries (Canada, Colombia, United States, and Zim-

babwe) account for 99.5% of the world's production since the early 1700s [Sutphin and Page, 1986]. Deposits of the Merensky Reef type, of Hulbert *et al.*'s [1988] "stratabound" PGE deposit subclass, including those of the Bushveld, Stillwater, and Great Dyke (Zimbabwe) intrusions, are known to account for 96% of the world's PGE resources [Sutphin and Page, 1986, p. 7]. PGE mineralization of the Bushveld, Stillwater, and Great Dyke intrusions is described by Naldrett [1981]. Buchanan [1988] discusses in detail the geological associations, critical industrial uses, market conditions, mining geology, and exploration and evaluation guidelines for PGE resources.

The Layered Mafic Dufek Intrusion

As a mafic stratiform cumulate body of the Bushveld and Stillwater type, and rivaling the Bushveld in size (Table 1), the Dufek intrusion in the Pensacola Mountains of Antarctica [Ford, 1976, Figure 1] might be expected to have resources similar to those bodies. (The name of the intrusion has been formalized to Dufek "Complex" by some authors [e.g., de Wit, 1985; Buchanan, 1988], but as that usage is inconsistent with nomenclature convention [North American Commission on Stratigraphic Nomenclature, 1983, p. 861], it is not followed in this report.)

Pyroxenitic units occur in the Dufek intrusion [Ford,

TABLE 1. Comparison of Areas of Layered Intrusions

Layered Intrusion	Area, km ²
Bushveld Complex (South Africa)	66,000
Dufek intrusion (Antarctica)	50,000+
Duluth Complex (USA)	4,715
Stillwater Complex (USA)	4,400
Muskox intrusion (Canada)	3,500
Great Dyke (Zimbabwe)	3,265
Sudbury Complex (Canada)	1,342
Skaergaard intrusion (Greenland)	104

From *Bonini* [1982] and, for Dufek, *Behrendt et al.* [1981]. The area of the Stillwater is misleading, as it is structurally tipped to vertical, and an original horizontal area, as approximately for the others, is unknown.

1976] but differ from the Bushveld's pyroxenitic Merensky Reef [*Naldrett*, 1981] in lacking chromitite, sulfides, and pegmatoidal phases. No unit comparable to the Merensky has been found in the Dufek intrusion, and if one exists, it is probably in the basal concealed section. However, the great size of the body, as inferred from geophysical surveys (Figure 1) and the many broad

petrologic similarities with the Bushveld and Stillwater complexes [*Ford and Himmelberg*, 1990] have attracted much speculation on the potential occurrence of PGE resources [e.g., *Wright and Williams*, 1974; *Zumberge*, 1979; *Lovering and Prescott*, 1979; *Auburn*, 1982; *Golden*, 1982; *Gjelsvik*, 1983; *Rowley et al.*, 1983; *Mitchell*, 1983; *Mining Journal*, 1985; *Shapley*, 1985, p. 135; *Pyne*, 1986, p. 355; *Fifield*, 1987, p. 57; *Parsons*, 1987, p. 85; *MacKenzie*, 1988; *Heylman*, 1989]. *De Wit* [1985] and *Beike* [1988] describe the operation and economic feasibility of a hypothetical platinum mine in a conjectural Merensky-type unit of the Dufek intrusion, which is discussed by *Auburn* [1986], *Spletstoeser* [1987], *Wyman* [1987], *Alabaster* [1988], and *Willan* [1989]. The Dufek intrusion lies within *MacKenzie's* [1988] "austral crescent," a zone *MacKenzie* expects will see an increasing focus of geopolitical activity related to resources.

The Dufek intrusion was discovered during 1957–1958 International Geophysical Year (IGY) geographical and geophysical explorations of ice shelves bordering the southern Weddell Sea [*Neuburg et al.*, 1959; *Aughenbaugh*, 1961; *Walker*, 1961]. In 1965 and several follow-

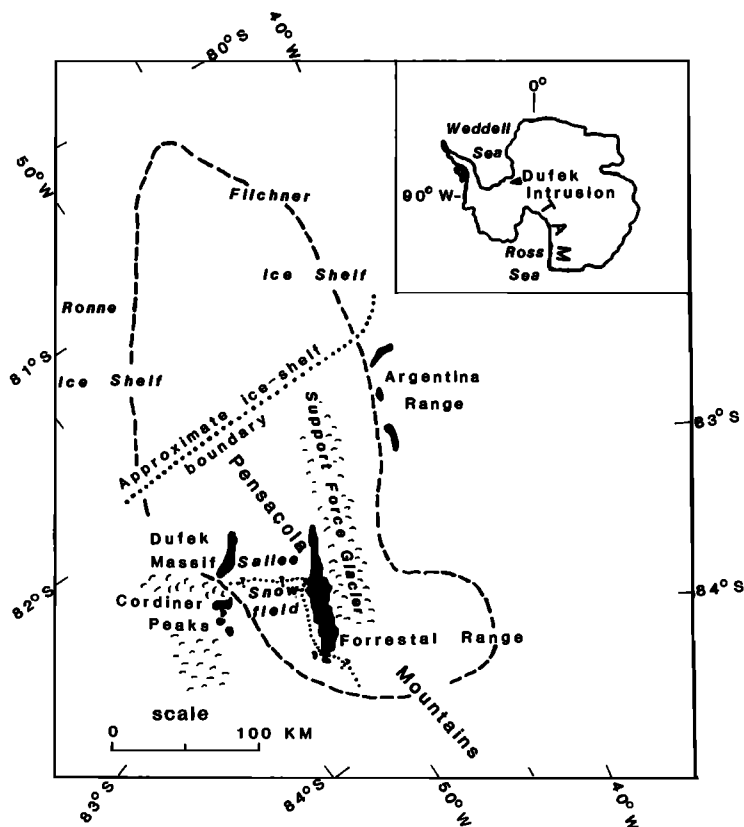


Fig. 1. Index map of Dufek intrusion showing location in Antarctica. Dashed lines show outline under ice inferred from geophysical surveys of *Behrendt et al.* [1981], and dotted lines are based on geologic mapping of *Ford et al.* [1978b]. Chief outcrop areas, black. TAM, Transantarctic Mountains.

ing summers it was explored by U.S. Geological Survey field parties, and in 1976 and later it was explored by USSR parties from Druzhnaya Base.

Presently available data on PGE and other possible resources of the Dufek intrusion [Ford *et al.*, 1983; Ford, 1983b] are of only reconnaissance type and an outgrowth of scientific study. This report provides a comprehensive bibliography on the Dufek intrusion and summarizes studies of its geology, geophysics, and petrology. Results of studies by the Soviet Union are not known to the author. Other reports in this volume treat the economic potential (de Wit) and mining aspects (Beike) of the intrusion. The Dufek intrusion is described in more detail by Ford [1976], Himmelberg and Ford [1976], and Ford and Himmelberg [1990].

REGIONAL SETTING

Sedimentary Sequences

The Dufek intrusion was emplaced in a long-lived, recurrently active mobile belt adjoining the craton of East Antarctica. Reconnaissance (1:250,000) geological mapping of this part of the Pensacola Mountains [Schmidt and Ford, 1969; Ford *et al.*, 1978a, b; Schmidt *et al.*, 1978] has shown that the sedimentary country rocks of late Precambrian to Permian age belong to three sequences separated by angular unconformities. The rocks are poorly exposed in the vicinity of the intrusion but are well exposed in the Neptune Range to the south (Figure 2).

The oldest sequence, of late Precambrian age, consists of possibly thousands of meters thickness of metagraywacke, slate, and pillow basalts of the Patuxent Formation. Graded bedding and sole markings typical of turbidites are common in the Patuxent. The unit is unconformably overlain by the Middle Cambrian [Palmer and Gatehouse, 1972] trilobite-bearing Nelson Limestone and silicic volcanic and volcanoclastic rocks of a Cambrian caldera complex [Schmidt *et al.*, 1978], which comprise the second sequence.

The third sequence consists mostly of sandstone and siltstone of Ordovician (?) to Permian age. It includes the Ordovician (?)–Devonian (?) Neptune Group; the Devonian Dover Sandstone; the Permian (?) Gale Mudstone (tillite); and the Pecora Formation, which contains Late Permian *Glossopteris*-bearing coal beds [Schopf, 1968]. The rocks of the third sequence belong to the Beacon Supergroup found throughout the Transantarctic Mountains [Barrett *et al.*, 1972].

Paleoenvironments in this area thus varied from a marine trench in the late Precambrian and a marine shelf in the early Paleozoic, to continental, glacial, and lacustrine in the late Paleozoic, with volcanism of principally basaltic type occurring in the late Precambrian and of silicic type related to caldera activity in the Late Cambrian [Schmidt *et al.*, 1978].

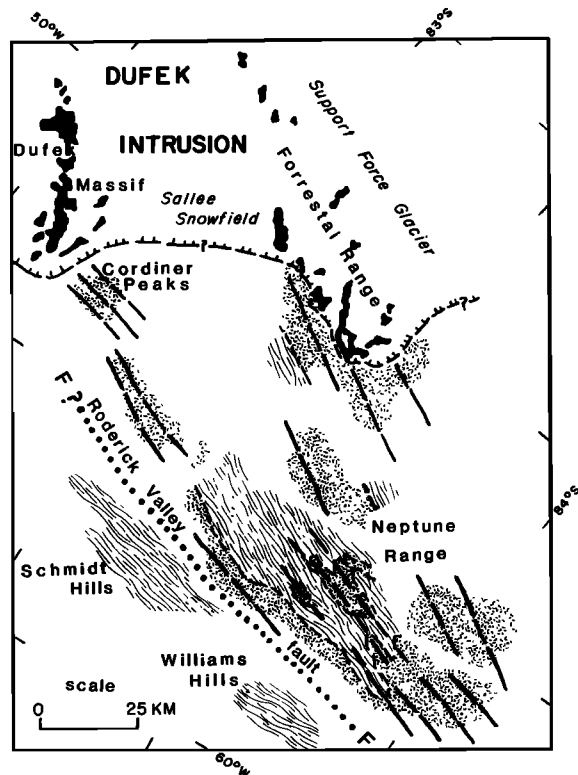


Fig. 2. Sketch geologic map of northern Pensacola Mountains. Hatched line shows southern contact of Dufek intrusion (chief outcrop areas, black). Broken wavy lined areas, Patuxent Formation; stippling, Paleozoic formations; heavy dashed lines, major fold axes; dotted line, Roderick Valley fault. From Schmidt and Ford [1969].

Orogenic Record

The angular unconformities between the sedimentary sequences mark major deformational events approximately correlative with orogenies recorded at many places in the Transantarctic Mountains. Strong folding and greenschist-facies metamorphism of the Patuxent Formation are correlated with the latest Precambrian Beardmore orogeny. Strong folding of the Cambrian rocks, intrusion of granite, and uplift and erosion correlate with the early Paleozoic Ross orogeny [Schmidt *et al.*, 1978]. A third orogeny, the probably Triassic Weddell orogeny [Ford, 1972], occurred prior to emplacement of the Dufek intrusion and resulted in locally strong folding of rocks of the third sequence.

The southern area of exposure of the Dufek intrusion lies entirely within the belt of the deformed Beacon Supergroup (Figure 2) close to East Antarctica's craton margin. Geophysical studies indicate a sharp transition from thin crust of West Antarctica to thicker East Antarctic crust across the area [Behrendt *et al.*, 1974]. The setting of the Dufek intrusion in a young mobile belt marginal to a craton contrasts with the intracratonic

settings of the Bushveld and other large layered mafic intrusions [Wager and Brown, 1967].

Relation to the Jurassic Ferrar Magmatism and Gondwana Rifting

K-Ar dating indicates a Middle Jurassic age of the Dufek intrusion [Ford and Kistler, 1980]. It was emplaced during the dominant phase (175–170 Ma) of the voluminous tholeiitic magmatism of the Ferrar Group dolerite sills and associated flood basalts found throughout the Transantarctic Mountains [Elliot *et al.*, 1985]. The tholeiitic magmatism was related to Transantarctic rift events, but the nature of rifting is controversial [Elliot, 1976; Cox, 1978; Ford and Kistler, 1980; Kyle *et al.*, 1981; Behrendt, 1983; Schmidt and Rowley, 1986]. Major north trending high-angle faults of the area (e.g., Roderick Valley, Figure 2; Enchanted Valley, Figure 3) may be related to this Jurassic rifting.

Jurassic tholeiite of Antarctica forms two distinct geochemical provinces, according to Faure *et al.* [1972]: (1) that of the Transantarctic Mountains, characterized by high SiO₂ (about 55%) and high initial ⁸⁷Sr/⁸⁶Sr, or *r_i* (0.708–0.714); (2) that of Queen Maud Land and nearby, characterized by lower SiO₂ (50%) and lower *r_i* (0.702–0.708). Jurassic hypersthene tholeiite dikes and sills near the Dufek intrusion are geochemically similar to those of the Transantarctic Mountains and unlike the Jurassic tholeiites of the Queen Maud Land region [Ford and Kistler, 1980]. Ford and Kistler [1980] suggest that rift origins of the two subprovinces of the Jurassic magmatism in Antarctica are markedly different: the Pensacola Mountains tholeiites (and the Dufek intrusion?) being related to a failed continental (Transantarctic Mountains) rift arm, and the Queen Maud Land and nearby tholeiites (and the South African Karoo Dolerites of similar age) being related to a completed ocean ridge system between Antarctica and Africa.

FORM AND SIZE OF THE DUFEK INTRUSION

Geophysical Studies

Geophysical studies [e.g., Behrendt, 1962, 1971; Behrendt *et al.*, 1966, 1979] show that the exposures of the intrusion in the Dufek Massif and Forrester Range near the body's southern end comprise only a few percent of its extent (Figure 1). The 1965–1966 aeromagnetic and gravity surveys by Behrendt *et al.* [1974] showed the intrusion to underlie the 50-km-wide Sallee Snowfield (Figures 2 and 3). Behrendt *et al.* [1974] also reported IGY magnetic data suggesting a possible continuation north to the ice-covered Berkner Island near Filchner Ice Shelf: an extension confirmed by 1978–1979 tracking of magnetic anomalies that show a minimum area of the intrusion to be about 50,000 km² [Behrendt *et al.*, 1980,

1981]. The magnetic anomalies have not been completely mapped.

Aeromagnetic anomalies are generally low, about 100γ or less, and show little pattern over the western end of Dufek Massif [Behrendt *et al.*, 1973a], where the lowest-exposed, magnetite-poor rocks of the intrusion crop out. Aeromagnetic intensities increase to about 400γ over the eastern end of the massif in the Davis Valley area and to more than 1000γ over the Forrester Range [Behrendt *et al.*, 1973a, b]. Magnetic susceptibility data are given by Beck and Griffin [1971]. Detailed gravity and radio echo ice-sounding surveys have located an ice-covered contact in the vicinity of Dufek Massif [England and Nelson, 1977]. The high regional magnetic anomaly over the Pensacola Mountains recorded from MAGSAT satellite data [Ritzwoller and Bentley, 1982, p. 287] is probably attributable chiefly to the Dufek intrusion.

Paleomagnetic studies [Griffin, 1969; Beck, 1972; Beck and Griffin, 1971; Beck *et al.*, 1968, 1979; Burmester and Sheriff, 1980; Burmester and Beck, 1981] show a paleomagnetic pole position similar to that of the Jurassic Ferrar Group, and the presence in some cumulate layers of field reversals that seem to be reflected in the linear pattern of mixed negative and positive aeromagnetic intensities in some areas.

Form of the Intrusion

The overall apparent structure defined by internal layering of the body is that of a broad syncline (Figure 3 and Ford [1976]). The 5°–10° southeast dipping homoclinal layered sequence of Dufek Massif forms part of a west limb that projects southeastward beneath Sallee Snowfield. Stratigraphically equivalent rocks (not necessarily the same layers, which individually may laterally terminate) are inferred to extend eastward and underlie the Forrester Range. Geophysical studies by England *et al.* [1979] show an eastward thickening of the body across part of Sallee Snowfield. A northeast trending synclinal axis follows the length of the Forrester Range, where the youngest differentiates (Lexington Granophyre) are exposed. The unexposed east limb of the syncline presumably underlies Support Force Glacier and other nearby ice-covered areas.

Evidence for either primary or secondary origin of the synclinal structure is equivocal. A tectonic origin, originally believed possible [Ford, 1968; Ford and Boyd, 1968], is suggested by an approximate parallelism between structural features of the body (microshears; fold axis) and regional structures of country rocks to the south (Figure 2) [Ford, 1972]. However, paleomagnetic studies [Burmester and Sheriff, 1980] support a primary rather than tectonic origin of the syncline.

Layered intrusions typically show a synclinal or funnel structure [Loney and Himmelberg, 1983]. Original

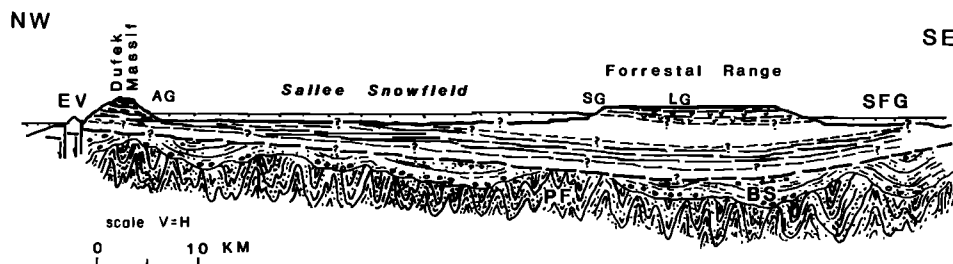


Fig. 3. Sketch cross section across southern end of Dufek intrusion. Concealed sections unpatterned. PF, Patuxent Formation; BS, Beacon Supergroup; EV, Enchanted Valley fault zone; SFG, Support Force Glacier. From Ford [1976].

horizontality of the layering is commonly assumed, but a mechanism of primary downdip growth of layers, or "downdip accretion" [Irvine *et al.*, 1983], might have produced the moderate Dufek inclinations of 10° or less. However, this mechanism would be expected to produce layers dipping inward from all walls to form a broad funnel structure (layers in southern parts of Dufek Massif and the Forrestal Range do not dip northward off the nearby concealed southern wall). Paleomagnetic data [Burmester and Sheriff, 1980], although compatible with a primary dip origin, only show that the layering attitudes originated prior to cooling through the Curie temperatures of the magnetic minerals. It is thus possible that the synclinal structure formed by some secondary mechanism before the magnetic pole orientation became fixed.

A secondary origin for the syncline by subsidence of the intrusion after it was largely solidified but still at elevated temperatures, as in the La Perouse intrusion of Alaska [Loney and Himmelberg, 1983], is compatible with the paleomagnetic data. A chaotic-appearing layer of megabreccia in the Forrestal Range may mark an event such as sudden subsidence [Ford *et al.*, 1979]. Late-stage subsidence along the syncline axis would account for orientations of microshears as far away as Dufek Massif that parallel the syncline axial plane [Ford and Boyd, 1968]. Subsidence may have accompanied withdrawal of magma from below and emplacement above into the Dufek's reservoir of late-stage fractionated magma (petrologic evidence for magma addition at this stage is discussed below).

The general outer form of the Dufek intrusion is poorly known. The contact as geologically mapped south and west of the Forrestal Range differs in detail from that inferred from geophysical surveys (Figure 1), which suggests that the intrusion underlies the sedimentary rocks of the area. A body of this immense size might be expected to be more complex in character than the exposed simple, single synclinal structure (Figure 3). In this regard, the Bushveld Complex was originally thought to be an essentially single large intrusion but is now believed on the basis of gravity data and the

strongly lobate outline of the complex to consist of four partly overlapping, broad funnel-shaped intrusions that are generally nonconnecting at depth [Hunter, 1978; von Gruenewaldt, 1979].

As now known, the areal extent of the Dufek intrusion is broadly elliptical in shape and shows only one eastward extending small lobe in the ice-covered region southeast of the Forrestal Range (Figure 1). However, most of this area is inferred from aeromagnetic anomalies that chiefly reflect magnetite-bearing rocks. Other ice-covered areas with weak magnetic signature might be underlain by rocks with few or no magnetic minerals, such as those of the western part of Dufek Massif. Outer parts of lobes, if present, would be expected to consist of weakly magnetic early differentiates, such as in the Dufek Massif, and lobe interiors to consist of iron-enriched later differentiates like those of the Forrestal Range. Detailed gravity or other geophysical surveys are needed to investigate the true form of the body, particularly in search for centers of thicker rock that might show a composite structure as in the Bushveld Complex.

Volume of the Dufek Intrusion

The uncertainties in size and form make any estimate of magma volume only a crude approximation. Present petrologic data [Himmelberg and Ford, 1976; Ford and Himmelberg, 1990] provide no clear evidence for the formation of the body from other than a single, large magma chamber, though with at least one major late-stage magma addition (discussed below). If the intrusion has a sheet form (Figure 3) and is 8–9 km thick (estimated from the southern area of exposure [Ford, 1976]), a minimum volume might be as large as $400,000 \text{ km}^3$. If multiple irruptive centers are present, depths to floor would be highly variable and a total volume would vary accordingly.

STRATIGRAPHY AND LITHOLOGY

General Comments

Mineral compositions, structures, and textures of the Dufek intrusion indicate an origin by fractional crystal-

lization, with mineral accumulation and solidification dominantly from the base upward. The nomenclature of *Irvine* [1982] for cumulates, which are the dominant rocks of the intrusion, is generally followed in this report. According to *Irvine* [1982], a "cumulate" is an igneous rock characterized by a framework of generally touching mineral grains (cumulus crystals) that were concentrated primarily by fractional crystallization. Cumulates are named according to decreasing abundance of cumulus minerals, as in "plagioclase-augite-pigeonite cumulate," a common type in the Dufek intrusion and one for which a conventional name generally would be gabbro or gabbronorite. Conventional names are also used in this report, as in "gabbroic cumulate."

The Dufek intrusion is subdivided into rock stratigraphic units as shown in Figure 4. Two nonoverlapping stratigraphic parts of the intrusion are exposed (Figure 3): a lower one, the "Dufek Massif section," consisting of early but not earliest cumulates (unexposed); and an upper one, the "Forrestal Range section," consisting of Fe-enriched later cumulates and overlying granophyre.

The Fe enrichment upward through the intrusion is reflected in generally upward increasing magnetite content and rock densities [*Ford and Nelson*, 1972] and rock [*Ford*, 1969, 1975] and mineral [*Himmelberg and Ford*, 1976] chemical variations.

Dufek Massif Section

The lowest exposed part of the intrusion consists of an about 1800-m thickness of generally well layered, mostly gabbroic cumulates that make up all of Dufek Massif and nearby nunataks. The two principal units are the 230-m-thick Walker Anorthosite and the overlying Aughenbaugh Gabbro (Figure 5). The Walker Anorthosite consists chiefly of uniform appearing, well-laminated plagioclase cumulates, with local thin layers containing cumulus pyroxene. The higher part of the Walker Anorthosite is conspicuously layered, and the contact with the overlying Aughenbaugh Gabbro is sharp.

The Aughenbaugh Gabbro consists predominantly of

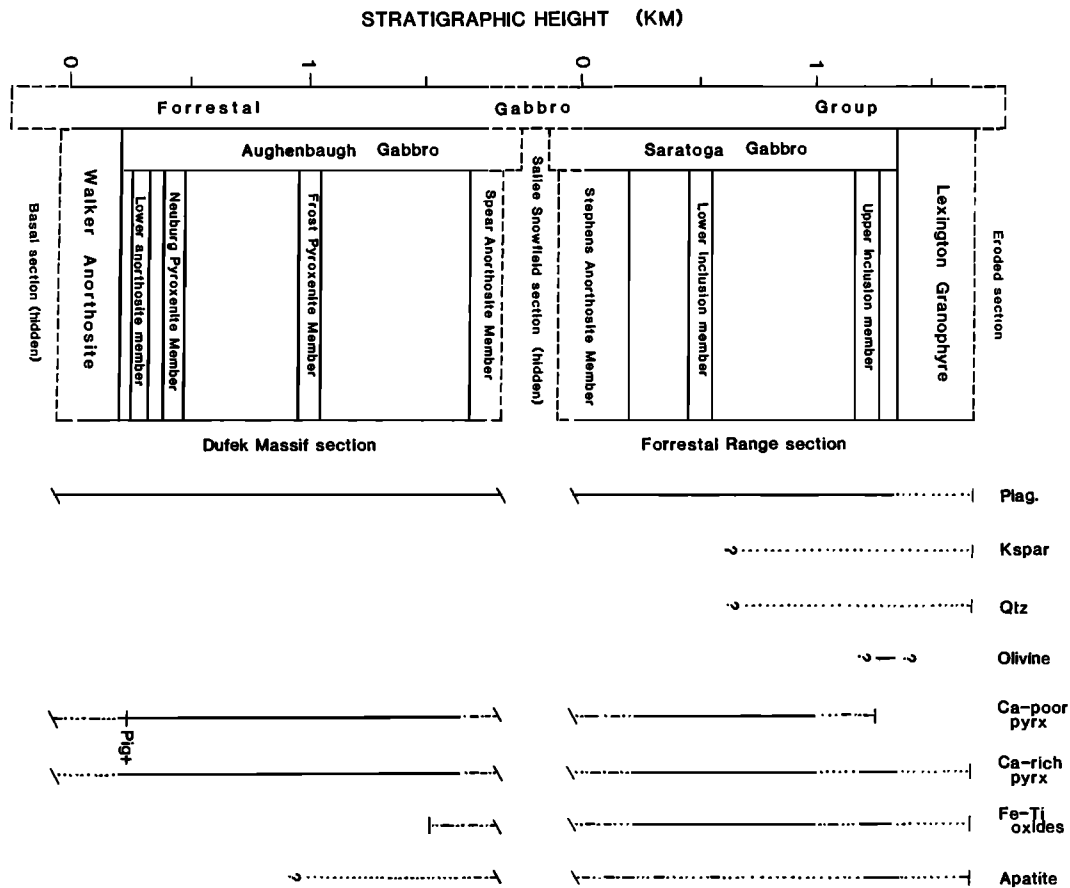


Fig. 4. Rock stratigraphic nomenclature of the Dufek intrusion and approximate mineral ranges. Minerals: solid lines, cumulus range; dashed lines, postcumulus and noncumulus; Pig+, lowest cumulus pigeonite or inverted pigeonite. From *Ford* [1976] and *Ford and Himmelberg* [1990].



Fig. 5. Aerial view south of Walker Peak showing the light-colored layered cumulates of the Walker Anorthosite (small center outcrop) below the darker Aughenbaugh Gabbro. Thin dark layer halfway up in the Aughenbaugh is the Neuburg Pyroxenite Member (about 200 m above the contact with the Walker Anorthosite).

plagioclase-two pyroxene cumulate with well-developed planar lamination shown by plagioclase. The cumulus pyroxenes are augite and inverted pigeonite. The gabbroic cumulates in places contain conspicuous, thick, modally graded layers of pyroxene cumulate and plagioclase cumulate. The lowest pyroxenite, the Neuburg Pyroxenite Member (Figures 6 and 7), is a single major layer of modally graded pyroxene cumulate about 5 m thick that occurs about 200 m above the Walker Anorthosite [Ford *et al.*, 1977]. Multiple pyroxene cumulate layers make up the Frost Pyroxenite Member (Figure 8), about 600 m above the Neuburg Member. The Frost Member, about 43 m thick and consisting of at least six modally graded layers, is mapped for about 35-km distance with no discerned variations [Ford, 1976, p. 26]. The Spear Anorthosite Member at the top

of the Aughenbaugh Gabbro consists of three major, modally graded layers of plagioclase cumulate interlain with gabbroic cumulate. The first appearance of cumulus Fe-Ti oxide minerals is marked by a few thin (centimeter scale), conspicuously dark layers and laminae near the top of the Dufek Massif section.

Forrestal Range Section

An iron-enriched upper part of the intrusion makes up the entire Forrestal Range, in which cumulates and minor quartz dioritic noncumulates of the Saratoga Gabbro and the overlying noncumulus silicic Lexington Granophyre comprise a stratigraphic section about 1700 m thick (Figure 4). Most cumulates of the section contain Fe-Ti oxide minerals in the range 2–10 vol %.



Fig. 6. Neuburg Pyroxenite Member (dark layer on middle ground cliff) and multiple dark-layered Frost Pyroxenite Member in distance below summit of Neuburg Peak (far right). View southeast.

The Saratoga Gabbro is much more heterogeneously layered than the Aughenbaugh Gabbro of the Dufek Massif section.

Layering is conspicuous in most outcrops and is commonly due to cumulus concentrations of oxides in thin dark layers and laminae and of plagioclase in light-colored layers and laminae. The approximately 300-m-thick Stephens Anorthosite Member at the base of the Forrestal Range section contains four 7- to 15-m-thick modally graded layers of plagioclase cumulate which are associated with large current-formed trough structures [Ford, 1970]. Amounts of oxide minerals are highly varied, but the highest concentrations seem to be in the interval between the Stephens Anorthosite Member and the "lower inclusion member" (Figure 4). This interval contains abundant thin layers

and lenses (troughs?) of oxide-dominant gabbroic cumulates, as well as several thin layers and lenses of magnetite up to about 1 m thick. The exposed magnetite layers are considerably smaller and fewer than those in the Upper zone of the Bushveld Complex [von Gruenewaldt, 1973].

Rounded and embayed anorthosite and leucogabbro inclusions (autoliths) up to 3 m across are common in some parts of the Saratoga Gabbro. The rocks have noncumulus-appearing texture. The inclusions are particularly concentrated about 500 m above the base of the Saratoga Gabbro in an approximately 40-m-thick layer locally having the chaotic appearance of a megabreccia. The megabreccia layer may record a major event of turbulence in the magma chamber [Ford *et al.*, 1979]. It occurs at about the stratigraphic level of reversals in



Fig. 7. Neuburg Pyroxenite Member at its type locality below Neuburg Peak [Ford, 1976], showing its sharp base and imperceptible gradation into overlying gabbroic cumulate just below top of photo.

chemical trends of cumulus minerals [Himmelberg and Ford, 1976, 1977] that are inferred to show an influx of new magma [Ford and Himmelberg, 1990]. Whereas gabbroic cumulates below this layer contain abundant magnetite, those above contain only minor amounts of the mineral.

At the top of the Saratoga Gabbro, a unit about 50 m thick consists of noncumulus-textured mafic-rich diorite, quartz diorite, and possibly tonalite or granodiorite, with an unusual abundance of apatite (2–5 vol %) and much higher than normal P_2O_5 content (1.6 wt %) [Drinkwater *et al.*, 1986]. The unit shows similarities to the “sandwich horizon” near the top of the layered cumulates of the Skaergaard intrusion, which Wager and Brown [1967]

believe was formed by crystallization directly from a final magma without accumulation of minerals.

The 300-m-thick leucocratic Lexington Granophyre, with the approximate modal and chemical composition of granodiorite [Ford, 1970], is the latest known differentiate of the intrusion (the top of the body is eroded). The granophyre sharply and apparently concordantly overlies the mafic rock sequence.

Whereas cumulates of the Dufek Massif section have normal igneous oxygen isotopic compositions ($\delta^{18}O$ mostly 6.0–7.0‰), those of the Forrestal Range section are highly variable and lower ($\delta^{18}O$ mostly 0–6.0‰), and Rb and Sr compositions show similarly large differences [Ford *et al.*, 1986].



Fig. 8. Multiple pyroxenitic cumulate layers of the Frost Pyroxenite Member below summit of Neuburg Peak (right). Aerial view southeast. England Peak, far center.

Hidden Sections

Two principal hidden parts of the intrusion are (1) a basal section estimated to be 3.5–1.8 km thick below the Walker Anorthosite (Figure 4; *Behrendt et al.* [1974]) and (2) a 2- to 3-km-thick intermediate interval beneath Sallee Snowfield (Figure 4; *Ford* [1976]).

Basal section. Characteristics of the hidden basal section can only be inferred from limited geophysical data that suggest the presence of ultramafic rocks at depth [*Behrendt et al.*, 1974]. The occurrence of olivine (Fo_{59}) in a gabbro autolith possibly derived from a concealed contact zone may indicate that olivine was an early member of the magma crystallization sequence [*Himmelberg and Ford*, 1983].

An insight into the nature of this part of the intrusion

can be obtained from stratigraphic comparisons with the Bushveld Complex using the first appearance of cumulus minerals as correlation markers [*Ford*, 1983b; *Ford et al.*, 1983]. Possible differences in original magma compositions and crystallization histories make such comparisons highly uncertain. The cumulus appearance of magnetite, as used by *de Wit* [1985, p. 22], would be a good correlation marker. Magnetite first appears as a cumulus phase near the top of the Dufek Massif section. However, the horizon in the Dufek intrusion which is equivalent to the Bushveld's lowest major magnetite layer, used by *de Wit* [1985], occurs somewhere in the 2- to 3-km-thick section concealed under Sallee Snowfield, thus precluding stratigraphic comparisons. The lowest major magnetite layers of the Dufek intrusion may be

marked by the sharp increase in aeromagnetic intensities over Sallee Snowfield measured by *Behrendt et al.* [1973a]. Based on the first appearance of cumulus pigeonite [*Himmelberg and Ford*, 1976], the lowest exposed rocks of the Dufek intrusion may be equivalent to a height about 1 km above the Merensky Reef and the cumulus terminations of Mg-olivine and chromite in the Bushveld Complex (*Ford* [1983b]; Figure 9).

Intermediate interval beneath Sallee Snowfield. Characteristics of the hidden Sallee Snowfield section can probably be inferred to be intermediate between higher rocks of the Dufek Massif and lower rocks of the Forrestal Range sections, assuming a single large intrusion which seems warranted by structural relations and chemical variations (Figure 10). In this interval, aeromagnetic intensities show little variation eastward across the snowfield until a sharp increase about 15 km west of the Forrestal Range [*Behrendt et al.*, 1973a], suggesting the ice-covered occurrence at that point of major layers of Fe-Ti oxide-rich rocks, probably magnetite, below the exposed Stephens Anorthosite Member.

MINERALS

General Comments

Plagioclase and two pyroxenes are the chief cumulus phases of the intrusion (Figure 4). Titaniferous magnetite and ferrian ilmenite are cumulus phases in most of the layered rocks of the uppermost part of the Aughenbaugh Gabbro, where only traces of oxides occur, and in the Saratoga Gabbro, where oxides are generally abundant. Apatite is a common though generally minor cumulus phase in the Saratoga Gabbro. Traces of sulfides are common, particularly in magnetite layers. Cumulus Fe-olivine has been found at only a single locality, near the top of the two-pyroxene range (Figure 4; *Himmelberg and Ford* [1976]). K-feldspar and quartz occur as postcumulus minerals in cumulus-mineral interstices only in the higher part of the layered sequence. An amesite occurrence is described by *Hall and Bailey* [1976].

Plagioclase

Plagioclase [*Abel*, 1978; *Abel et al.*, 1979; *Ford et al.*, 1980], generally zoned [*Haensel*, 1988; *Haensel et al.*, 1986], is the dominant cumulus phase throughout the sequence. Cumulus plagioclase is rare in the basal parts of the modally graded pyroxenite units of the Neuburg and Frost Pyroxenite members and in some thin layers and lenses of magnetite.

The anorthite content of grain cores generally decreases upward, from about An₇₉ in the lowest cumulates of the Walker Anorthosite to An₅₃ in highest cumulates of the Saratoga Gabbro and in the Lexington Granophyre (Figure 10). This fractionation trend is characteristic of layered mafic intrusions. The compositional range is very close to that of the Bushveld

Complex except that the highest Bushveld Upper zone rocks are more albitic (An₄₃₋₃₀) [*Wager and Brown*, 1967]. The reversals in plagioclase compositions in the Neuburg and Frost Pyroxenite members, the Stephens Anorthosite Member, and at about 700 m above the base of the Saratoga Gabbro are significant variations in the overall trend of plagioclase compositions.

Pyroxenes

Ca-rich pyroxenes persist stratigraphically throughout the intrusion, in contrast to the Ca-poor pyroxenes (Figure 4; *Himmelberg and Ford* [1973, 1975b, 1976]). Orthopyroxene locally occurs with augite as a cumulus phase in the lower 50 m of the Walker Anorthosite. No cumulus Ca-poor pyroxene is known to occur for the next 150 m of section, but it reappears at the base of the Aughenbaugh Gabbro as cumulus pigeonite. Ca-poor pyroxene mostly crystallized as pigeonite, but later much of it inverted to orthopyroxene. Cumulus pigeonite crystallized up to a level of 1100–1200 m in the Saratoga Gabbro, above which ferroaugite is the only cumulus pyroxene for the interval below the Lexington Granophyre [*Himmelberg and Ford*, 1976]. Subsolidus exsolution textures in the pyroxenes are typical of those of other stratiform intrusions described by *Wager and Brown* [1967]. The major chemical variation is in the proportions of Ca:Mg:Fe, which ranges from Ca₃₆Mg₄₉Fe₁₅ to Ca₃₀Mg₂₄Fe₄₆ for Ca-rich pyroxenes and Ca₄Mg₆₉Fe₂₇ to Ca₁₁Mg₃₄Fe₅₅ for Ca-poor pyroxenes [*Himmelberg and Ford*, 1976].

The general Fe enrichment of pyroxenes upward in the section (Figure 10) is interrupted by two principal irregularities: (1) a 1-km-thick section in the lower part of the Aughenbaugh Gabbro that shows little or no Fe enrichment and (2) a marked reversal from about 500 m to 700 m above the base of the Saratoga Gabbro, above which a trend showing Fe enrichment is renewed. The change from cumulus orthopyroxene to pigeonite coexisting with augite (as indicated by the most Fe-rich orthopyroxene) occurs at $Mg/(Mg + Fe) = 0.71$ [*Himmelberg and Ford*, 1976], which is almost identical to the compositions reported for the change in the Bushveld Complex [*Atkins*, 1969].

In the Saratoga Gabbro and Lexington Granophyre, a second, late-stage, set of Ca-rich and Ca-poor pyroxenes occurs in addition to the cumulus pyroxenes [*Himmelberg and Ford*, 1976]. The late Ca-rich pyroxenes are pale green in thin section and are part of an augite-ferroaugite series even richer in Ca than the cumulus series. They form patches within, and broad margins on, primary brown Ca-rich pyroxenes, with indistinct and irregular boundaries. The late-stage pyroxenes are characterized by numerous inclusions of hornblende, biotite, Fe-Ti oxide minerals, and relict

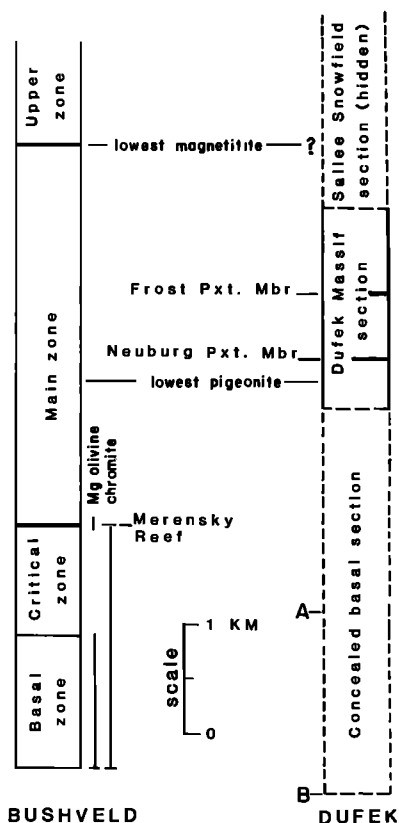


Fig. 9. Possible comparison of lower part of Dufek intrusion with Bushveld Complex based on lowest cumulus pigeonite (Fig. 4) as correlation marker. A and B (Dufek), Behrendt et al.'s [1974] minimum and maximum concealed basal section thickness estimates. From Ford [1983b] and Ford and Himmelberg [1990].

primary augite. Late-stage Ca-poor pyroxene is present in only minor amounts and forms a ferrohypersthene series with no evidence of inversion from pigeonite. It occurs mostly as discontinuous grains closely associated, and commonly intergrown, with hornblende, biotite, and pale green augite.

Olivine

Mg-rich olivine is a cumulus mineral in early fractionation stages of most tholeiitic layered intrusions (e.g., Fo₈₈₋₆₈, Bushveld Complex; Wager and Brown [1967]). In the Dufek intrusion, only relict cumulus-appearing olivine is found in a single specimen from the upper part of the Saratoga Gabbro (Figure 4). Its composition, Fa₉₅ [Himmelberg and Ford, 1976], is much more Fe rich than late-stage olivines (Fa₅₁₋₈₅) in the upper part of the Bushveld Complex but similar to compositions in the higher part of the Skaergaard's Upper zone [Wager and Brown, 1967]. Other specimens of the Saratoga Gabbro, as well as the Lexington Granophyre, contain minor

amounts of alteration products that appear to be secondary after olivine. The crystallization of the Fe-rich olivine at about the cessation of crystallization of two cumulus pyroxenes (Figure 4) is typical in layered intrusions [Wager and Brown, 1967].

Fe-Ti Oxides

Minor amounts of cumulus Fe-Ti oxide minerals form marked thin (centimeter scale) layers at about 200 m from the top of the Aughenbaugh Gabbro (Figure 4). Fe-Ti oxides are common in the Saratoga Gabbro, typically in modal amounts of 2–10%, and in places form layers and lenses up to about 1 m thick [Himmelberg and Ford, 1975a, 1977]. The oxides typically consist of complex, composite grains composed of a titaniferous magnetite host containing ferrian ilmenite lamellae par-

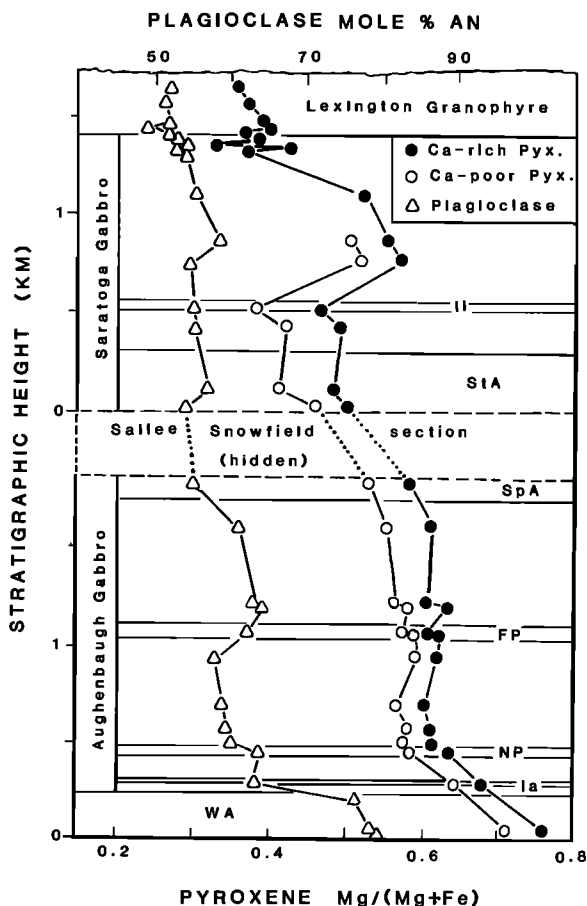


Fig. 10. Stratigraphic variation of cumulus plagioclase and pyroxene compositions in the Dufek intrusion. Unit designations (from base, Figure 4): WA, Walker Anorthosite; la, lower anorthosite member; NP, Neuburg Pyroxenite Member; FP, Frost Pyroxenite Member; SpA, Spear Anorthosite Member; StA, Stephens Anorthosite Member; li, lower inclusion member. From Himmelberg and Ford [1976], Abel et al. [1979], and Ford and Himmelberg [1990].

allel to {111} (ilmeno-magnetite), which is intergrown with a coarse, irregular, optically homogeneous ferrian ilmenite [Himmelberg and Ford, 1977]. Himmelberg and Ford [1977] interpreted the Fe-Ti oxide textures as indicating the following different generations of titaniferous magnetite and ferrian ilmenite in the Dufek intrusion: (1) stage I, magmatic crystallization of a homogeneous titaniferous magnetite and, for samples containing discrete ilmenite grains, a coexisting ferrian ilmenite; (2) stage II, subsolidus "granule exsolution" of the primary titaniferous magnetite to form composite grains of titaniferous magnetite (of lower ulvospinel content than the primary grains) and ferrian ilmenite; and (3) stage III, subsolidus exsolution of stage II titaniferous magnetite to form ferrian ilmenite lamellae in a titaniferous magnetite host.

The titaniferous magnetites of stages I and II are not preserved. Ti and Fe contents of the oxide minerals are largely controlled by subsolidus recrystallization and thus generally show no stratigraphic variations that can be related to magma differentiation. However, fractionation trends are shown by V_2O_3 and Al_2O_3 contents of ilmeno-magnetite [Himmelberg and Ford, 1977]. For example, the V_2O_3 content of ilmeno-magnetite near the top of the Aughenbaugh Gabbro is 2.21 wt % and decreases to 0.50 wt % at about 425-m height in the Saratoga Gabbro. Al_2O_3 contents correspondingly decrease from 2.29 wt % to 1.59 wt %. At a height of about 750 m in the Saratoga Gabbro, V_2O_3 content increases to 1.28 wt % and then decreases upward to 0.11 wt % in ilmeno-magnetite of the highest cumulates below the Lexington Granophyre. The Al_2O_3 contents of ilmeno-magnetite correspondingly decrease from 2.24 wt % to 1.40 wt % in this interval. Thus both V_2O_3 and Al_2O_3 contents show a reversal in trend with height somewhere in the stratigraphic interval of 425 m to 750 m in the Saratoga Gabbro. This reversal may be correlated with reversals in the compositional trends of Ca-rich and Ca-poor pyroxenes and plagioclase (Figure 10) that probably reflect a major addition of new magma at a late differentiation stage [Ford and Himmelberg, 1982].

Apatite

Apatite occurs in trace or larger amounts throughout the Dufek intrusion. It is a trace postcumulus phase in the Dufek Massif section, except for appearing cumulus in the Spear Anorthosite Member. Cumulus apatite occurs in minor amounts in the Stephens Anorthosite Member and is abundant, up to 2–5 vol %, only in a 65-m-thick interval of gabbroic cumulates about 30 m below the Lexington Granophyre [Drinkwater et al., 1986]. Apatite occurs in three principal forms: (1) prismatic, euhedral cumulus grains that parallel lamination and layering; (2) subhedral or anhedral postcumulus grains that are generally larger than the cumulus grains

and occupy areas between cumulus silicates and oxides; and (3) acicular noncumulus grains in granophyre and other noncumulates. Preliminary microprobe analyses show compositions similar to fluorapatite of other layered intrusions. Occurrences of cumulus apatite in the Stephens and possibly the Spear Anorthosite members show earlier crystallization of this mineral than typical [Wager and Brown, 1967].

Sulfides

Trace or larger amounts of sulfide minerals occur throughout the layered sequence. Sulfides are markedly more abundant in the Forrestal Range than in the Dufek Massif. Sulfide distribution is variable along as well as across layers. Chalcopyrite and pyrite or pyrrhotite are dominant [Drinkwater et al., 1985]. Bornite (?) is also reported [Walker, 1961]. Bright green efflorescences of secondary atacamite are common. Occurrences in the Forrestal Range and the Dufek Massif are different.

In the Dufek Massif, traces of sulfides are mostly in or near xenolithic inclusions, suggesting a contamination origin. Sulfides are much more common in the Forrestal Range, generally in amounts up to about 3 vol % (maximum found, 12 vol %). Sulfides in the Forrestal Range occur commonly as interstitial space fillings between cumulus silicates and oxides, as inclusions within oxide grains, as fracture fillings, and more rarely as possible replacement stringers and patches in altered postcumulus amphibole and biotite. The sulfides are generally concentrated in and near thin layers of magnetite, particularly in an interval from about 200 m to 500 m above the base of the Saratoga Gabbro. Sulfides are also concentrated in an interval 200–500 m below the Lexington Granophyre.

The sulfides of the Forrestal Range are generally similar in occurrence and amount to those of the Upper zone of the Bushveld Complex, in which sulfur saturation of the magma and separation of small quantities of immiscible sulfide liquid are related to lowering FeO content of the magma during formation of magnetite-rich layers [von Gruenewaldt, 1976, 1979].

THE RESOURCE QUESTION

There is no direct evidence for the presence of economic minerals in the Dufek intrusion. However, the world's large stratiform mafic igneous intrusions generally contain economically significant deposits of one or more metals. For example, the Bushveld Complex, which is the richest, has yielded immense wealth from Pt, Pd, Cr, Ni, Cu, V, Ti, Fe, and other commodities [Willemse, 1969]. The Dufek intrusion is poorly known. Thus none of the types of deposits found in similar bodies can be arbitrarily excluded as possible resources. If resources are found, the many political and logistical problems in this remote polar area will probably dampen

enthusiasm for near-future commercial exploration. *De Wit* [1985], on the other hand, optimistically describes an operation of a hypothetical platinum metal mine at the Dufek Massif, drawing on comparisons with mining activities in other polar areas.

Many factors hinder a realistic estimation of the Dufek's resource potential, chiefly its general concealment by ice and lack of a directed minerals search. Materials of high unit value, such as PGE, would be of principal exploration interest in the foreseeable future [Ford, 1983a, b]. Present information on possible resources is limited to indirect results from mostly reconnaissance scientific studies such as described in this report. Factors involved in the origin of PGE deposits in layered intrusions include the following: composition of original magma [Naldrett, 1981; Irvine and Sharpe, 1982], nature of cumulus processes and contamination [Irvine et al., 1983], addition and mixing of magmas [Campbell et al., 1983], and composition and processes in mantle source regions and derivative basaltic magmas [Hamlyn et al., 1985]. These factors are little known for the Dufek intrusion.

The composition of the original Dufek magma(s?) is a principal uncertainty in the appraisal of possible resources. The geochemical nature of the magma cannot be inferred from the small exposure of contact rocks, which show "chilling" of Fe-rich fractionated magma [Ford, 1970]. Alternately, the compositions of apparently comagmatic undifferentiated bodies are taken to represent an original composition of layered intrusions [e.g., Jackson, 1971]. The original Dufek magma may accordingly be represented by nearby Ferrar dike and sill compositions [Ford, 1974]. This tholeiite, however, contains much less MgO and more SiO₂ than the estimated Bushveld original magma [Irvine and Sharpe, 1982], but the significance of such differences is unclear.

The Neuburg and Frost Pyroxenite members, which are the most mafic-rich units of the intrusion and most closely resemble the 1- to 10-m-thick PGE-rich pyroxenitic Merensky Reef of the Bushveld Complex, are the most attractive units for resource speculation. However, the pyroxenites and all other analyzed rocks of the Dufek Massif section contain amounts of PGE only near or below determinability limits (10 ppb Pt, 4 ppb Pd, 5 ppb Rh) by fire assay methods used [Ford et al., 1983]. Minor amounts of PGE have been found in a variety of lithologies scattered through the intrusion, with maximum amounts of only 35 ppb Pt, 44 ppb Pd, and 12 ppb Rh, all in the Saratoga Gabbro [Ford et al., 1983]. Present studies have not yielded indications of PGE or any other metal concentrations of economic significance. The maximum known PGE amounts are insignificant in comparison with those (20,000–30,000 ppb) of the Stillwater's J-M Reef deposits [Page et al., 1985].

Possible guides for PGE exploration of the Dufek intrusion are chiefly from studies of similar bodies

elsewhere. Soil sampling and geochemistry were used in locating the Stillwater's J-M Reef [Buchanan, 1988], and stream sediment panning located the Bushveld's Merensky Reef. Lack of soils and placers, however, precludes PGE prospecting by such traditional methods for the Dufek intrusion.

Future prospecting of the Dufek intrusion will be difficult and will require innovative and probably expensive techniques, such as extensive outcrop sampling and using geochemical associations with elements less costly to analyze. For example, the strong correlation between V and PGE (Figure 11) suggests that V might be a useful "pathfinder" for geochemical exploration in exposed parts of the intrusion [Ford et al., 1983]. V is principally contained in oxides, and the positive correlation between PGE and modal amounts of oxides (Figure 11) suggests that oxide-rich units of the Forrestal Range would be of principal exploration interest in exposed parts of the body.

The collection of PGE from magmas chiefly by sulfide melts [Naldrett, 1981; Campbell et al., 1983; Buchanan, 1988] in fractionated, late Fe-rich magma [Parry, 1984] probably accounts for the relatively higher PGE values found in the Forrestal Range where sulfides are most abundant. The mixing of residual and added magma, which is recorded in the middle part of the Forrestal Range section, can also be a factor in PGE concentration [Campbell et al., 1983]. Although this part is probably the most attractive for PGE exploration of exposed parts of the intrusion, the concealed section of early cumulates beneath the Walker Anorthosite probably holds the chief resource potential [Ford et al., 1983; Ford, 1983b; de Wit, 1985; Buchanan, 1988], based on comparison with the Bushveld Complex (Figure 9).

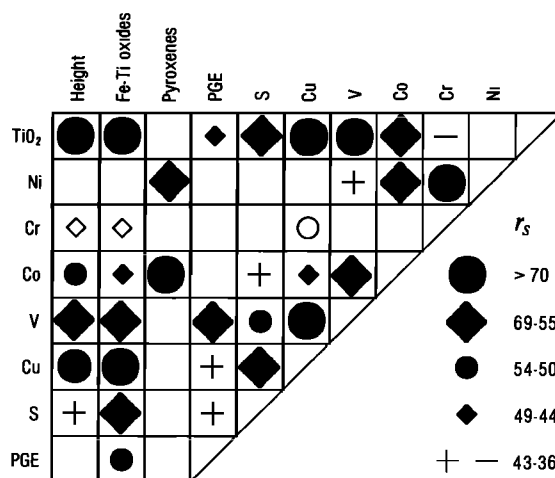


Fig. 11. Element correlations in cumulates of the Dufek intrusion. Solid symbols, positive Spearman rank correlation coefficient (r_s); open symbols, negative. From Ford et al. [1983].

Elliot [1985, p. 58] remarks: "For the mining geologist, the Dufek is unquestionably the prime target in Antarctica: whether it has either chromite seams sufficiently thick or platinum-bearing horizons of sufficient grade to be economically exploited is in the realm of speculation. Only by drilling will this ever be known." Rowley [1989] disagrees and believes that gold in the Antarctic Peninsula is a better mineral exploration target. Plans for eventual drilling of the Dufek intrusion were discussed in U.S. congressional hearings in 1979 (E. P. Todd, in *Committee on Energy and Natural Resources, United States Senate* [1979, p. 8]). In the event of such future large-scale activities occurring in this region, Parker *et al.*'s [1977] study provides some baseline data for monitoring environmental effects.

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THE ECONOMIC POTENTIAL OF THE DUFEEK COMPLEX

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A geological and geochemical comparison of the Mesozoic Dufek and Proterozoic Bushveld complexes reveals substantial similarities between these two mega layered intrusions. In particular, their tectonic setting, isotopic characteristics, and history of differentiation, including the presence of "reversals" which are indicative of magma addition, can be closely matched. In the Bushveld Complex, magma addition and mixing are the primary causes for the large platinum group element (PGE) and chromite deposits, and this may well be the case in the Dufek Complex. Nevertheless, the Dufek magmas differed from those of the Bushveld Complex in that clinopyroxene was probably always an important liquidus phase and the precipitation of chromite was suppressed. The probable lack of chromite in the Dufek Complex would preclude the presence of chromite-hosted PGE deposits such as the UG2 of the Bushveld Complex. If chromite was essential for PGE precipitation, the Dufek would be a poor prospect. However, the Merensky Reef type of deposits are probably the product of large-scale magma mixing with concomitant immiscible sulfide precipitation. The presence of chromite in this type of deposit is apparently a response to the mixing process and not essential to the formation of sulfides. We estimate the probability of a Merensky Reef-type PGE deposit in the Dufek Complex to be about 75%. Should such a deposit be realized, then, given the present-day platinum price, economic models indicate that it could be profitably mined.

INTRODUCTION

The Dufek Complex is a very large mafic layered intrusion which was discovered during geographic and geophysical exploration of the inner reaches of the Filchner and Ronne ice shelves in 1957, the International Geophysical Year. Since then, it has been widely recognized that this intrusion may well contain significant concentrations of "strategic" ore deposits; however, the recognition of this complex as a possible "storing house" for important economic minerals is largely conjectural. It is based on geological and mineralogical comparisons of collected rock samples with similar rocks that occur in layered intrusions elsewhere and whose immediate relations to important mineral-bearing layers within these intrusions are well known (see *de Wit* [1985] and *Shapley* [1986] for overviews). The best known and most studied example of such an economic mineral-rich mafic layered intrusion is the Proterozoic (2.05 Ga) Bushveld Complex of South Africa. Chromitite layers with associated platinum group elements (PGE) are confined to the lower parts of this intrusion, as are sulfides of nickel, copper, PGE, and cobalt, while magnetitite with associated vanadium occurs at higher levels.

The relative location of economically valuable minerals can be predicted given detailed knowledge of the mineralogical and chemical variations throughout the layered sequences as a whole. The application of these techniques has a great bearing on reliable prediction and location of such ore deposits. For example, exploration for PGE in the Stillwater Complex of Montana in the United States was initially modeled on such a comparison of its geological and petrological similarities with those of the Bushveld Complex. This comparative approach has successfully stood the "test of time": 1987 saw the inauguration of mining of the United States' first major source of PGE and the first shipment of concentrate from the Stillwater mine. It is of ironic significance for Antarctic environmentalists to note that the first batches of marketable palladium, platinum, and rhodium (three of the PGEs) have now been produced from a mine which is situated in a previously declared wilderness area of great natural beauty and relative inaccessibility (Custer National Forest land adjacent to the Bear Tooth Wilderness Area); here the environmental opposition proved of no avail.

In this paper a similar, if somewhat more theoretical, approach of "comparative science" is taken. The sim-

ilarities between the Dufek and Bushveld complexes are carefully weighed against their differences. In essence, this task is more difficult than was the case for the Stillwater Complex, because there are very limited data available for the Dufek Complex. Nevertheless, these scientific comparisons are the best means available at present to build a framework from which to further evaluate the economic potential of the Dufek Complex. This paper is thus divided into two sections: the first, a scientific assessment for potential PGE ore resources; the second, an economic assessment for potential PGE ore reserves of the Dufek Complex. (Reserves are currently exploitable resources of specific value to mankind. The phrase "value to mankind" needs some explanation. Whatever the economic or political structure of the world in which a mineral deposit is worked, there will always be some criteria by which the effort put into exploiting it may be compared with the incentive for doing so [Dixon, 1979].)

POTENTIAL ORE RESOURCES OF THE DUFEK COMPLEX: A SCIENTIFIC ASSESSMENT

The Bushveld and Dufek complexes are the two largest known mafic layered intrusions of their kind in the world (with the possible exception of the almost unknown (~2.0 Ga) Cunene Complex in southern Angola). The Bushveld Complex also hosts the largest known deposits of platinum group elements, chromium, and vanadium on Earth. Other significant products of this intrusion are nickel and copper. The associated felsic rocks have large tin and fluorite deposits.

The magmatic processes responsible for this vast accumulation of rocks and associated ore deposits are analogous to those that have operated during the accumulation of the Dufek Complex. It is therefore reasonable that the Bushveld Complex may serve as a well-studied analog for the relatively poorly known Dufek Complex.

To be able to use the Bushveld Complex as an analog and predictive tool for estimating the economic ore potential of the Dufek Complex, the available data on the similarities and differences between them have to be clearly understood. The tectonic setting, geology, and petrology are compared and contrasted below, which allows areas of potential economic mineralization to be identified.

Tectonic Setting

The Dufek Complex straddles the enigmatic boundary between the two vastly different geological (tectonic) provinces of East Antarctica and West Antarctica (Figures 1 and 2a). The former constitutes the cratonic part of the continent: the Dufek Complex intrudes the extreme edge of this province, and it is likely that at least part of the basement below the Paleozoic sediments

consists of Proterozoic and possibly even Archean continental lithosphere. The presence of Archean cratonic rocks may be important, as the Archean lithospheric mantle may be abnormally enriched in PGE [Groves *et al.*, 1987; de Wit and Tredoux, 1988]. The Dufek Complex is part of a much larger volcano-plutonic igneous province, remnants of which occur along the entire Transantarctic Mountains and in Tasmania, as well as in southern South America and Africa (Figure 1). The rocks of this province were all emplaced within a relatively short time span during a period when these continents were still grouped together as Gondwana; the continental magmatism (~170–190 Ma) [Allsopp *et al.*, 1984a, b; Schmidt and Rowley, 1986; Kyle *et al.*, 1980] preceded the onset of seafloor spreading in the southern Indian and Atlantic oceans (~150 Ma) by about 20–40 Ma. The Dufek Complex was intruded at about 170 Ma (mid-Jurassic) into deformed Devonian-Permian sediments [Elliot, 1972; Faure *et al.*, 1972; Ford and Kistler, 1980].

The disposition of the volcano-plutonic rocks in Antarctica suggest that the Dufek Complex was part of a complex continental rift that existed from about 160 to 180 Ma along the entire Antarctic-Tasmanian line and Queen Maud Land (Figure 1). It has been suggested that there has been significant transform faulting (500- to 1000-km displacement) along the length of this rift, and much (local?) extension may have been parallel rather than across the length of the rift during the early stages of its development [Schmidt and Rowley, 1986; Storey and Nell, 1988]. Thus the local tectonic setting of the Dufek Complex was one of a transtensional intracontinental rift developed during the initial breakup of Gondwana, which preceded large-scale ocean floor formation, the development of a complex triple junction in the south Atlantic, and separation of several microplates which constitute West Antarctica, away from the cratonic East Antarctica.

An "Atlantic-type" rifted continental margin may thus be invoked, and in such a setting, the Dufek Complex might be compared to that of the Skaergaard Complex (Greenland), which formed near the hinge line between undeformed and extended continental lithosphere [see White *et al.*, 1987]. On a larger scale and in a Gondwana context, however, this Antarctic intracontinental rift formed behind an active subduction zone and calc-alkaline volcanic arc which now constitutes much of the Antarctic Peninsula (West Antarctica) and the southern Andes. In such a tectonic environment, the Dufek Complex would have been intruded into a back-arc transform rift, perhaps comparable to the Gulf of California.

The early "precursor" history of the Karoo uplift and volcanism overlaps with the closing stages of the Cape Fold Belt formation (215 Ma) [Halbich *et al.*, 1983], tectonism which can possibly be linked to shallow upper

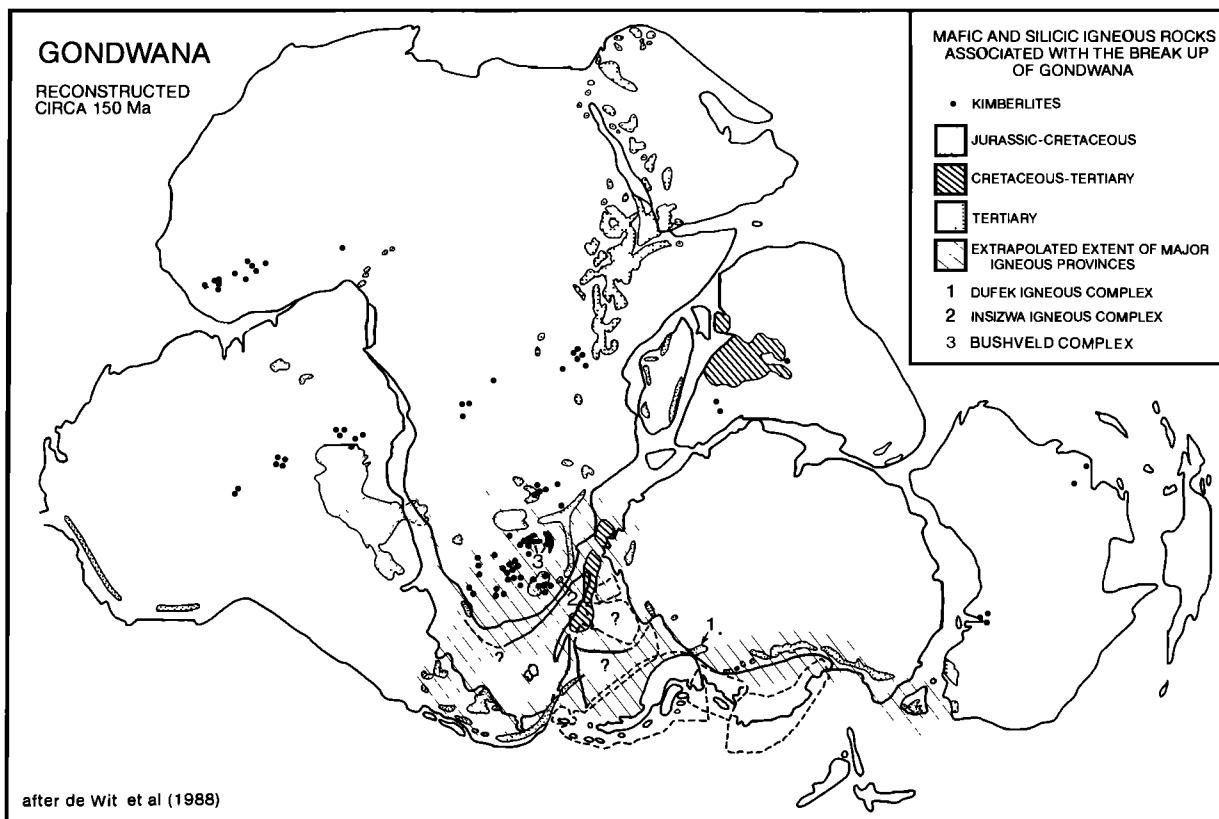


Fig. 1. Map of Gondwana, showing the location of the Dufek and Bushveld complexes. The Dufek Complex is part of a major igneous province, as shown, related to the Mesozoic breakup of Gondwana. The complex is intruded close to the boundary between cratonic East Antarctica and the young orogenic West Antarctica.

Paleozoic subduction along Gondwana's Pacific margin [de Wit, 1977; Lock, 1980]. Furthermore, remnants of the vast mid-Jurassic back-arc extensional volcano-tectonic province of southern South America [Bruhn *et al.*, 1978] are present in the offshore Orange Basin [Dingle *et al.*, 1983]. This substantiates suggestions of a link between Mesozoic subduction along the Pacific margin of Gondwana and the early rifting phase of the southern Atlantic [Cox, 1978; de Wit and Stern, 1981]. Thus in a broad tectonic framework, the Dufek Complex was intruded in a region of crustal transtension as a back-arc process, just prior to a large-scale dispersion of continental fragments (Figure 2a).

A similar tectonic setting can be invoked for the Bushveld Complex at the time of its intrusion into the early Proterozoic (deformed) sedimentary host (the Transvaal Supergroup) covering the Archean cratonic basement of Southern Africa. It was bordered to the west by rocks of the Kgalagadi tectonic foreland fold and thrust belt (Figure 2b). This belt may have been coupled to a calc-alkaline/accreted-terranes province to the northwest and possibly the ~2.0 Ga Richtersveld

calc-alkaline subprovince to the southwest [de Wit, 1987]. Considerable (wrench) faulting is thought to have occurred during the intrusion of the Bushveld Complex [Hartnady *et al.*, 1985; du Plessis and Walraven, 1987]. Thus the Bushveld Complex and its regionally related intrusions may be mid-Proterozoic ensialic back-arc phenomena similar to the Dufek Complex. The current data base is too small to rigorously prove this suggestion, but the similarities are nevertheless fairly marked.

Geology and Stratigraphy

Like the Dufek Complex, the Bushveld Complex is a megaintrusion which covers an area of some 65,000 km². The rocks occupy an irregular basinlike depression surrounded by the relatively undeformed sedimentary and volcanic rocks of the Transvaal Supergroup and the basement rocks of the Kaapvaal craton. The central part of the basin is occupied by felsic rocks including the Rooiberg felsites and Stavoren granophyre, which formed the roof to the crystallizing mafic magmas, and the Nebo granite, which intrudes through

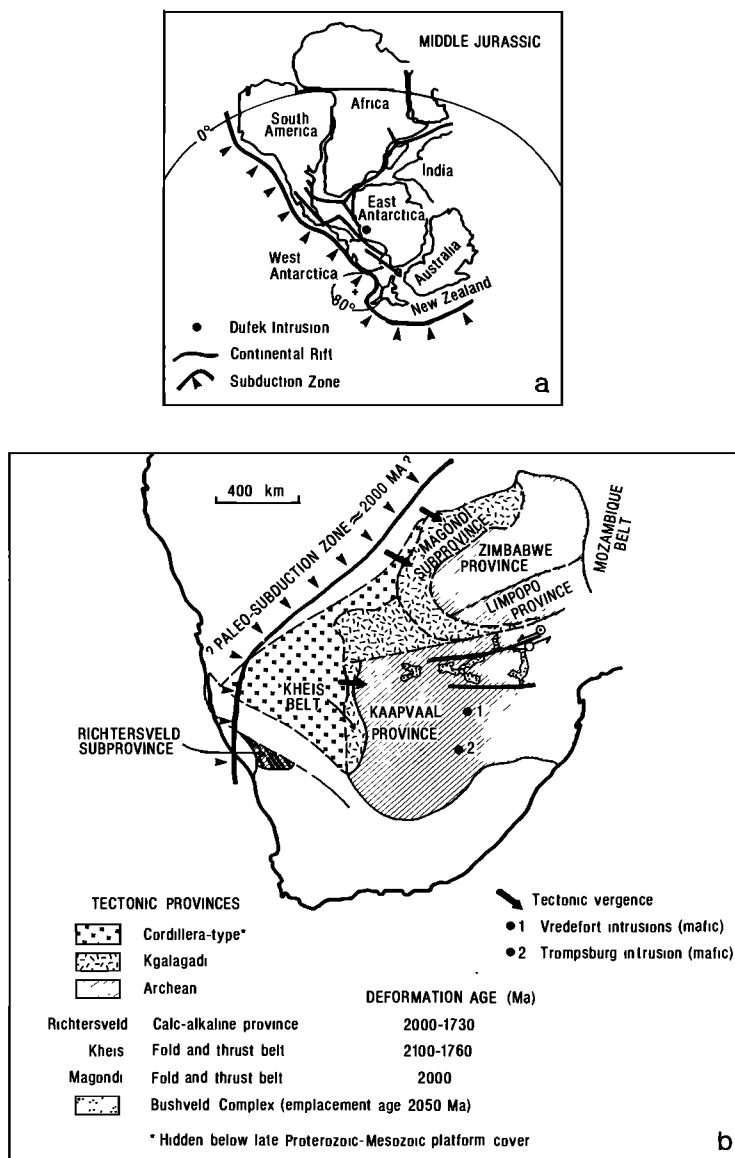


Fig. 2. (a) Tectonic setting of the Dufek Complex in a Gondwana framework ~170 Ma. (b) Tectonic setting of the Bushveld Complex in a cratonic framework of southern Africa ~2.0 Ga. From Hartnady *et al.* [1985].

the whole succession and thus postdates the mafic layered suite [Walraven, 1986]. The mafic rocks now form arcuate masses that surround the felsic core. The whole of the Bushveld Complex, including the late-stage granites, intruded at ~2050 Ma [Hamilton, 1977; Kruger *et al.*, 1987; Walraven, 1988].

The eastern lobe of the Bushveld Complex (~9 km thick) serves as an analog for the Dufek Complex, but it should be realized that the considerably thinner (6.3 km) western lobe could also serve this purpose. The mafic suite of the Bushveld Complex has been subdivided on

mineralogical grounds into five major units: the marginal, lower, critical, main, and upper zones [Walraven, 1986] (Figures 3 and 5). The marginal zone comprises a diverse suite of fine-grained rocks of pyroxenitic to gabbroic composition [Willemse, 1969; Sharpe, 1981; Cawthorn *et al.*, 1981] which form sills and other small intrusions in the floor rocks of the complex. This irregular thin "skin" is considered by some workers to represent relatively pristine samples of the magmas that formed the layered suite [Sharpe, 1981; Cawthorn *et al.*, 1981; Harmer and Sharpe, 1985]. The marginal zone

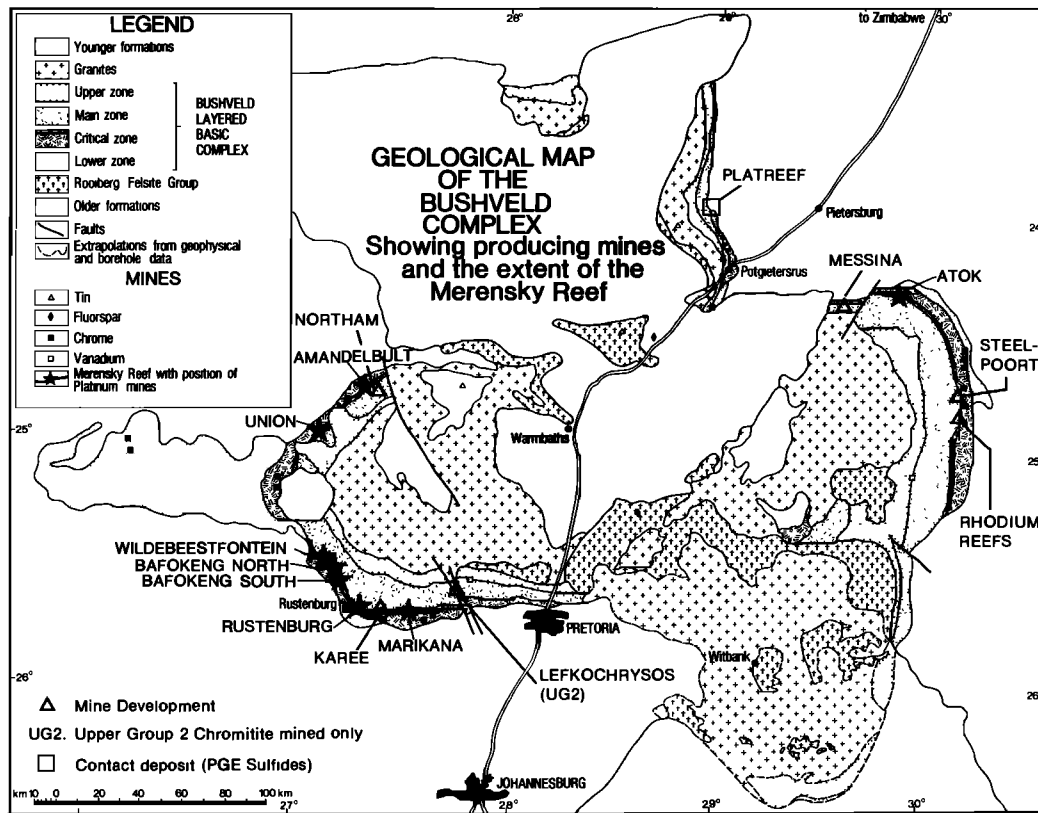


Fig. 3. Map of the Bushveld Complex showing the operating mines and those under development. Note the six new mines under development since the *de Wit* [1985] study, several of which are geared to exploit the UG-2 deposit.

rocks of the Bushveld Complex can be compared to possible parental magma of the Dufek intrusion (the Ferrar dolerites as a whole and the Cordiner Peak dykes in particular [Ford and Kistler, 1980]).

In this work, however, we are concerned mainly with the other four layered units. The lower zone consists mainly of peridotites and orthopyroxenites; the overlying critical zone consists of a lower pyroxenitic group of rocks and an upper noritic group. There are numerous important chromite layers within this latter unit including the LG-6 which is extensively mined for chromite and the UG-2 which has significant concentration of PGE in addition to chromite. The latter is mined extensively for PGE by the Western Platinum Mine and will be mined exclusively at the new Lefkochrysos Mine (recently renamed the Crocodile River Mine; Figure 3). The critical zone is capped by the well-known Merensky cyclic unit with its associated PGE, Cu, and Ni mineralization (the Merensky Reef; see Figure 4) mined in all the mines except Lefkochrysos. The main zone comprises a thick sequence of gabbro-norites without marked cyclic or other modal layering, but cryptic layering is quite well developed (Figure 5) and there is a

significant variation in Sr isotope initial ratios (Figure 6). The upper zone is also a thick sequence of rocks, the lower boundary of which is marked by the well-known pyroxenite marker [Kruger *et al.*, 1986, 1987]. The upper zone is characterized by its relatively iron-rich nature, and it consists predominantly of ferrogabbro-noritic rocks, but marked modal layering occurs which includes a number of vanadium-bearing titaniferous magnetite layers, the most important of which is the main magnetite layer. This zone is also very well differentiated from bottom to top (norites to ferro-diorites), as is shown in Figure 5.

The Dufek Complex is not as well known as the Bushveld Complex, but it is similar in size. A combined aeromagnetic and radio echo ice-sounding survey indicates a minimum area of over 50,000 km² for the intrusion compared with the ~66,000 km² for the Bushveld Complex [Behrendt *et al.*, 1974, 1980]. In addition, the presence of large-amplitude magnetic anomalies to the north and east of the surveyed area is suggestive of an even greater extent [Behrendt *et al.*, 1980]. The intrusion is estimated to be about 8–9 km in thickness [Ford, 1970; Ford and Boyd, 1968]. The Bushveld and

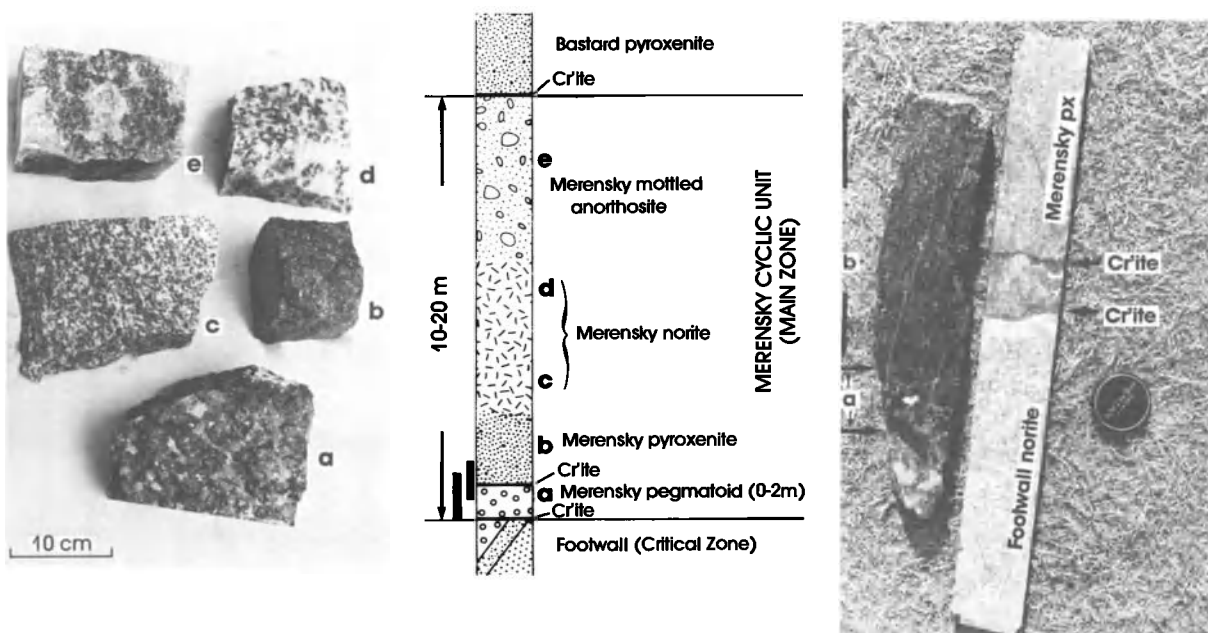


Fig. 4. The Merensky cyclic unit and the location of the Merensky Reef in different parts of the Bushveld Complex. Vertical black bars indicate the mined part at different localities. Note that the Merensky pegmatoid (a) may be very much thinner or considerably thicker than the minimum mining width (76 cm). The Merensky Reef (mined part) may include the whole or part of the Merensky pegmatoid and part of the Merensky pyroxenite. The most richly mineralized part of the Merensky Reef is usually one or both of the thin chromite (cr'tite) stringers (1-4 cm) which sandwich the pegmatoid.

Dufek complexes are similar in size and are thus at least an order of magnitude larger than other PGE-bearing mafic layered intrusions (for example, the Stillwater Complex, Montana, United States).

The cumulates of the Dufek Complex are exposed in two partial nonoverlapping stratigraphic sections (Figure 7). The lowermost 1.8 km of exposed rocks makes up the Dufek Massif section, and the upper exposed section forms the Forrestal Range. The combined thickness of these two sections and the intervening part covered by the Sallee Snowfield is estimated to be 6 to 7 km [Ford, 1970], and the geophysical evidence [Behrendt *et al.*, 1980] suggests that there is another 1.8 to 3.5 km of unexposed basal portion. The total thickness of ~7 to 9 km is, therefore, comparable to that of the Bushveld Complex (Figure 5).

The Dufek Massif section of the intrusion is mainly gabbro-noritic in character, whereas the Forrestal Range section is ferro-gabbro-noritic to dioritic in composition with abundant magnetite [Himmelberg and Ford, 1977]. These two sections can be broadly correlated with the main and upper zones of the Bushveld Complex, respectively (see de Wit [1985] and Figure 5).

Petrology

Layered intrusions as large as the Bushveld and the Dufek complexes are invariably intruded as a series of

magma inputs and not a single large influx. Evidence for this includes reversals in the orderly progression of mineralogical and chemical changes that result from the differentiation of a magma. These reversals are usually indicated when the composition of minerals such as plagioclase and pyroxene changes abruptly to indicate a new influx of higher-temperature magma. Plagioclase becomes more calcic and pyroxenes more magnesian. High-temperature minerals such as olivine may also suddenly reappear in the succession. In the Bushveld and Dufek complexes, such reversals are evident from the published data (see Figure 5). These reversals are of vital importance to the economic evaluation, because PGE deposits in the Bushveld Complex are associated with the abrupt new magma inputs marked by the reversals. Magma inputs can also be identified using other techniques such as the Sr isotope variations, which may fingerprint the input of a contrasting magma type from a different source area or one that has had a different history from the resident magma in the chamber.

The recognition of such contrasts in magma composition are extremely important: the major PGE-producing layer in the Bushveld Complex, the Merensky Reef, is associated with a large influx of new magma. This new influx is not clearly evident in the mineralogical parameters discussed above because the

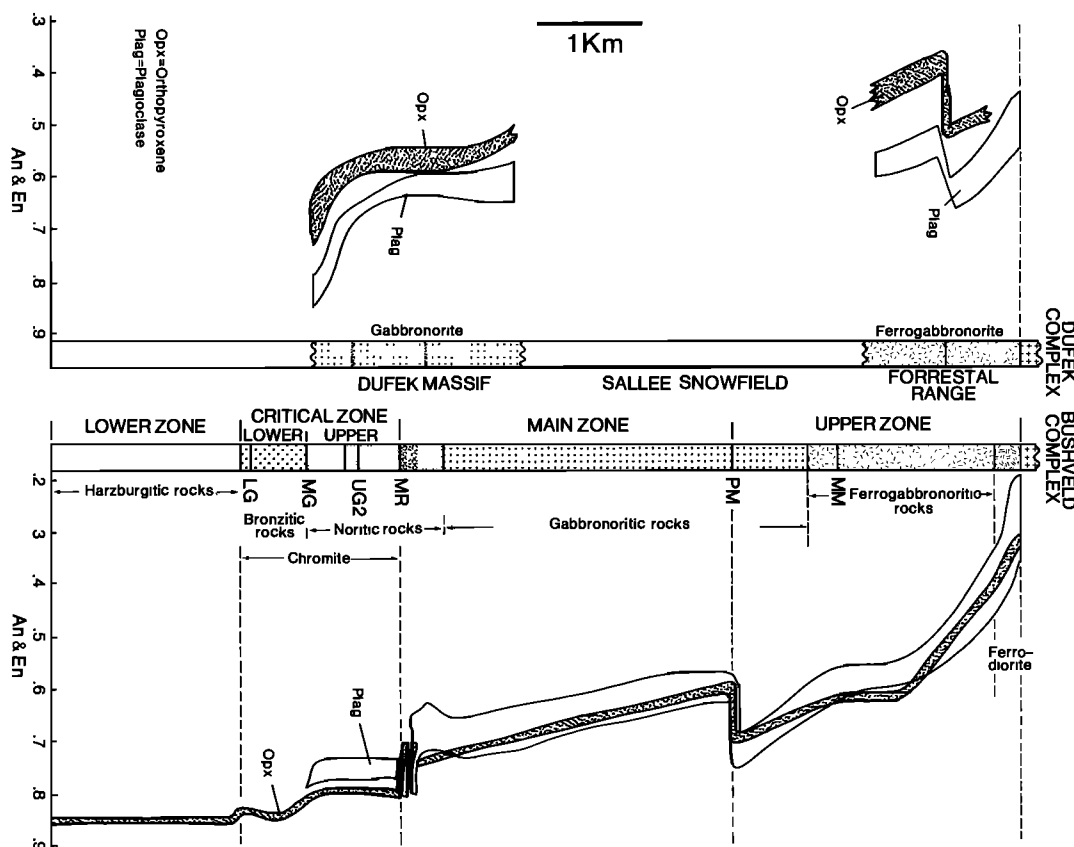


Fig. 5. Summary of comparative mineralogy of the Bushveld and Dufek complexes. This diagram shows the An content of plagioclase and the En content of orthopyroxene. Note the sympathetic variation of these two parameters which indicates the progress of differentiation as well as the presence of major magmatic influxes. This is especially evident at the pyroxenite marker of the Bushveld Complex and in the Forrestal Range section of the Dufek Complex. Note, however, that the major influx of magma at the Merensky unit does not show a reversal. The thick section of rocks covered by the Sallee Snowfield shows very little differentiation, and a major reversal or series of small reversals similar to that in the Forrestal Range section are probably present. Data from *Himmelberg and Ford* [1976], *Cameron* [1978, 1980, 1982], *Kruger and Marsh* [1985], *Mitchell* [1986], and *Molyneux* [1974]. For further discussion, see text.

new magma had a major element composition similar to that already present, but the isotope systematics clearly prove this new magma input (see below) [Kruger and Marsh, 1982; Kruger et al., 1988; Sharpe, 1985]. Other indications of new magma influxes are the erosion and scouring of the previously deposited crystal pile, as is the case at the base of the Merensky Reef [Kruger and Marsh, 1985; Campbell, 1986; Eales et al., 1986, 1988]. Ford and Boyd [1968] indicate that large scourlike troughs occur near the base of the Frost pyroxenite member of the Dufek Complex, which may have a similar origin.

The available Sr isotope data from the Bushveld Complex show that these rocks have a wide range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Figure 6). This ratio is the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the rocks corrected for the

decay of ^{87}Rb to ^{87}Sr since the time of crystallization of the rocks and is a measure of the Rb/Sr prehistory of the source area of the magma. Source areas with a long-lived high Rb/Sr ratio will have an elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Rocks of asthenospheric mantle derivation (low Rb/Sr) would be expected to have ratios between 0.701 and 0.702 at the time of intrusion (2050 Ma). It is evident that the layered rocks have a relatively high and variable signature relative to typical mantle-derived rocks. Continental crustal materials (high Rb/Sr) of a similar age (granites, granodiorites, and tonalites) would be expected to have higher ratios (between 0.710 and 0.730). These observations suggest that the magmas that formed the layered sequence of the Bushveld Complex are the products of mixing of mantle-derived mafic magmas with assimilated lithospheric host rocks. It can

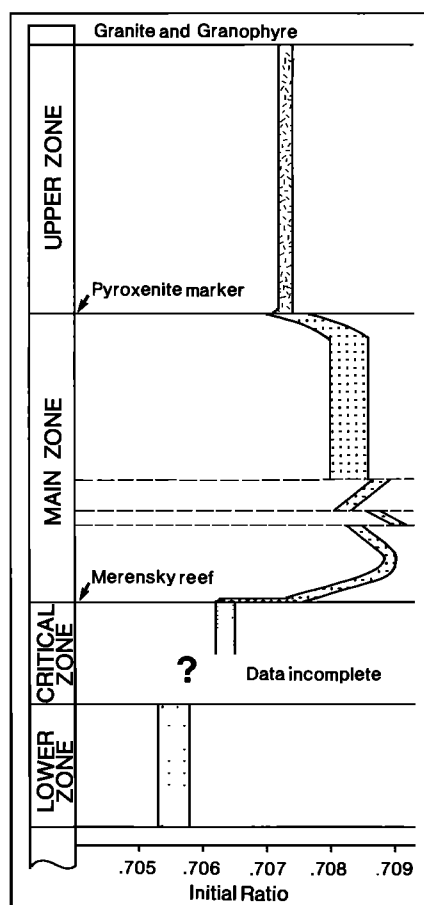


Fig. 6. Summary diagram showing the Sr isotopic variation in the Bushveld Complex. Note the two major isotopic discontinuities at the base of the Merensky unit and the pyroxenite marker, only one of which is evident in the mineralogical data of Figure 5. The data as a whole indicate significant source enrichment, but this is most clearly evident in the main zone. Data from Hamilton [1977], Kruger and Marsh [1982], Kruger *et al.* [1986, 1987, 1988], and Sharpe [1985].

be shown that this mixing process of mantle and crustal material occurred at source, prior to injection into the magma chamber, and the isotopic variation now observed in the layered rocks was due to injection of magmas with different crustal signatures into the magma chamber where further evolution occurred.

The isotopic stratigraphy of the Bushveld Complex is discussed in greater detail by Kruger [1988] but broadly corresponds to the four major stratigraphic subdivisions as illustrated in Figure 6. The data show that there is a general steplike upward increase in the initial ratios from the lower zone (0.7050–0.7056), to the critical zone (0.7060–0.7064), and to the main zone (0.7075–0.7090) [Hamilton, 1977; Kruger and Marsh, 1982; Sharpe, 1985; Kruger *et al.*, 1987, 1988, 1990].

The whole upper zone in the eastern and western parts of the intrusion has an initial ratio which is tightly constrained by isochron systematics to 0.7073 ± 1 [Kruger *et al.*, 1987]. This represents a reversal in the general upward increase of the initial ratio. The significance of the constancy of the initial ratio of the upper zone is that no further magma additions occurred after that which initiated the evolution of this zone at the pyroxenite marker [Kruger *et al.*, 1987].

In contrast, the main zone displays a considerable isotopic variation, even though the absolute values are generally high (Figure 6). This in turn implies that magmas with contrasting isotopic characteristics, but broadly similar chemistries, intermittently flowed into the chamber during the crystallization of the rocks. The volumes of magma that flowed into the chamber at the base and top of the main zone were very large, forming up to 80% of the magma in the chamber [Schiffries and Rye, 1989; F. J. Kruger, unpublished data]. Data on the lower and critical zones are relatively sparse at present, but in general these two zones have lower and more constant ratios than the main zone but not as constant as that of the upper zone. However, as more detailed data become available, the variations that there are will be resolved.

Very detailed isotopic data are now available on the two major isotopic discontinuities centered on the Merensky Reef and the pyroxenite marker, at the base and top of the main zone, respectively (Figure 6) [Kruger and Marsh, 1982; Sharpe, 1985; Kruger *et al.*, 1986, 1987, 1990]. The very abrupt change in the initial ratio across the Merensky unit implies that a major influx of new magma with a high (>0.7075) initial ratio occurred immediately prior to the formation of the Merensky Reef [Kruger and Marsh, 1982; Kruger *et al.*, 1990]. The overall upward increase in the initial ratio within the Merensky cyclic unit itself can be attributed to a "smoothing" effect of an initially sharp steplike isotopic discontinuity at the base of the unit. Such a steplike change has now been confirmed in the Northam and Brits areas [Kruger *et al.*, 1990]. The implication of these isotopic data for the PGE mineralization of the Merensky Reef is that the economically important metals were derived from the magma above the crystal pile during the intrusion and mixing event; this implication refutes the model of Ballhaus and Stumpfl [1986] in which significant mineralization due to upward infiltration is invoked. This very major abrupt (contaminated) magma influx, identified using Sr isotopes, is the prime reason for the existence of the exploitable PGE-rich Merensky Reef.

In contrast to the abrupt isotopic discontinuity at the Merensky Reef, the rocks in the main zone below the pyroxenite marker show a continuous change in the isotopic ratio over a stratigraphic interval of 200 m [Sharpe, 1985; Kruger *et al.*, 1986]. The pyroxenite

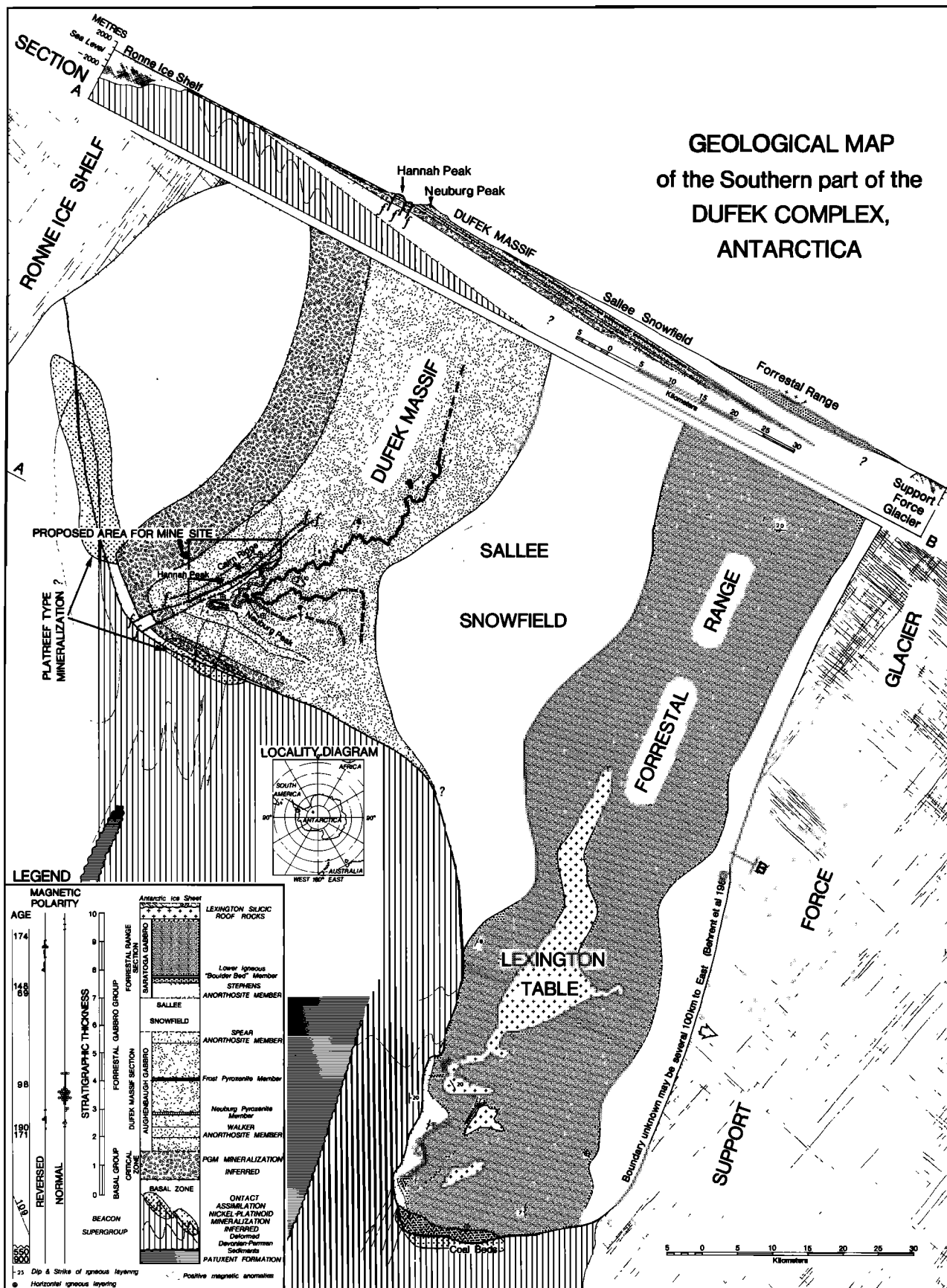


Fig. 7. Geologic map and section of the exposed part of the Dufek Complex. Also shown is the proposed location of the hypothetical Dufek Platinum Metals Mine [from de Wit, 1985].

marker itself marks the approximate position where change ceases and the isotopic character of the upper zone is fixed (Figure 6). This continuous change in the ratio is attributed to the slow continuous influx and thorough mixing of a new, low initial ratio magma with the resident magma, while crystallization of the rocks occurred [Kruger *et al.*, 1986]. The new influx terminated at the pyroxenite marker itself, and this marks the point where new magma ceased to be added to the magma chamber. The slow influx and mixing did not result in the production of an economically important layer, as an abrupt saturation and deposition of sulfides did not occur.

In contrast to the Bushveld Complex, published Sr isotope data are available on only a few samples [Faure *et al.*, 1972] from the Dufek Complex. Additionally, Kyle *et al.* [1980] report an unpublished communication that the initial ratio of the Dufek Complex (Forrestal Range section only?) is uniform at 0.709. Preliminary data from a more extensive project [Ford *et al.*, 1986] indicate that there may be extensive variation in the initial ratio (0.7076–0.7092). From an isotopic-geochemical point of view, these samples have relatively high initial ratios but are not as enriched as those from the main zone of the Bushveld Complex. They are more similar to the lower or critical zones. Nevertheless, like the rocks of the Bushveld Complex, these rocks are abnormally enriched in comparison with other mantle-derived rocks at the time of intrusion. A detailed isotopic comparison of the Dufek and Bushveld complexes awaits more extensive data.

In contrast to the Dufek Complex per se, there are a considerable amount of Sr isotopic data available on rocks of the Ferrar Supergroup tholeiites of which the Dufek Complex forms a part [Compston *et al.*, 1968; Jones *et al.*, 1973; Faure, 1981; Faure *et al.*, 1972, 1974, 1979, 1982; Hoefs *et al.*, 1980; Mensing *et al.*, 1984; Kyle *et al.*, 1980, 1983]. These rocks are characterized by extremely high and quite variable Sr initial ratios (0.709–0.715) relative to on-craton rocks of a similar age (the Kirwan volcanics of Dronning Maud Land, 0.702–0.708) [Faure *et al.*, 1979]. The high ratios of the Ferrar have been attributed to crustal contamination [Faure, 1981; Faure *et al.*, 1972, 1982; Hoefs *et al.*, 1980; Mensing *et al.*, 1984] as well as to an anomalously enriched (lithospheric) mantle source [Kyle, 1980; Kyle *et al.*, 1980, 1983]. It is evident that as the Dufek Complex forms part of the Ferrar Supergroup, and the magmas of the latter had high and variable initial ratios, that the Dufek Complex may have had parental magmas with a high and variable Sr isotopic signature. It is therefore probable that the isotopic stratigraphy of the Dufek Complex would indicate influxes of contrasting magmas as is the case in the Bushveld Complex. Moreover, it confirms that significant lithosphere contamination must also have been important.

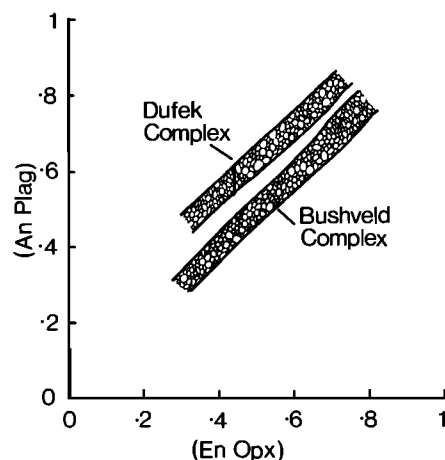


Fig. 8. The An content of plagioclase versus the En content of orthopyroxene. This indicates the very Ca-rich nature of the Dufek magmas relative to those of the Bushveld Complex. This Ca-rich nature results in the abundant modal clinopyroxene present in the Dufek Complex rocks.

As is shown in Figure 5, there are definite similarities between the Bushveld and Dufek complexes in terms of their stratigraphy and compositional parameters as well as their isotopic characteristics. However, there is one major difference. The Bushveld Complex is noritic to gabbro-noritic, whereas the Dufek Complex is gabbro-noritic to gabbroic in character. As is shown in Figure 8, for any given Mg/(Mg + Fe) ratio of the orthopyroxene, the plagioclase of the Dufek Complex is much more calcic than that of the Bushveld Complex. This appears to hold even where the plagioclase is most An rich at the base of the Dufek Massif section. Comparison of the major element chemistry of the mafic rocks of the Ferrar Supergroup [Elliot, 1972; Kyle, 1980; Ford, 1983] with that of possible parental magmas of the Bushveld Complex [Davies and Tredoux, 1985] indicates that this probably holds for all the possible parental magmas of the Dufek Complex. The Ca-rich nature of these Antarctic magmas implies that augite will probably always be a liquidus phase, even in the hidden part below the Dufek Massif section. For example, Kyle [1980] attributes most of the chemical variation in the Ferrar mafic rocks to fractional crystallization involving augite, pigeonite, and plagioclase. Augite has a strong affinity for Cr and thus suppresses the precipitation of chromite [Irvine, 1967; Eales *et al.*, 1980]. It is therefore doubtful that a significant precipitation of chromite (chromitite layers) could have occurred in the hidden zone below the Dufek Massif section. If this is the case, it may be futile to search for chromitite-hosted (UG-2 type) PGE deposits in the Dufek Complex. This idea is also supported by the low Cr contents of the Ferrar dolerites (59–142 ppm) [Kyle, 1980] compared with the

TABLE 1. Platinum Group Elements and Gold Tenor of Ores and Magmas

	Value
<i>Ores [Naldrett et al., 1987]</i>	
Tenor of sulfide	488 $\mu\text{g/g}$ PGE and Au
Tenor of ore	8 $\mu\text{g/g}$ PGE and Au
Thickness of ore	76 cm (minimum stope width)
Density of ore	3.4 g/cm^3
Unit area of stope, ore	258.4 g/cm^2 of ore
Unit area of stope, PGE and Au	2067 $\mu\text{g/cm}^2$ of PGE and Au
Unit area of stope, sulfide	$\sim 4.23 \text{ g/cm}^2$ (equivalent to 1.64 wt % of sulfide over the 76 cm of stope width)
<i>Magmas [Davies and Tredoux, 1985]</i>	
Magnesium basalt	36.8 ng/g (ppb)
Tholeiite basalt	21.4 ng/g
Density of magma	$\sim 2.6 \text{ g/cm}^3$

To provide 2067 $\mu\text{g/cm}^2$ of PGE and Au assuming 100% extraction requires (1) $2067/0.0368 = 56,174 \text{ g/cm}^2/2.6 \text{ g/cm}^3 = 216\text{-m}$ layer of magma or (2) $2067/0.0214 = 96,588 \text{ g/cm}^2/2.6 \text{ g/cm}^3 = 371\text{-m}$ layer of magma.

Bushveld Complex marginal zone rocks (373–917 ppm) [Davies and Tredoux, 1985].

All the PGE deposits in the Bushveld Complex including the Merensky Reef are associated with chromite. Some workers believe that precipitation of chromite is essential for the deposition of a PGE deposit (see Cousins and Vermaak [1976] for a brief review). If this is proven to be the case, the Dufek Complex would be a poor PGE prospect. This hypothesis is not proven, however, and Merensky-type PGE deposits may be purely process related (magma mixing) in which the precipitation of sulfide is important [Campbell et al., 1983]. The Ferrar dolerites have significant quantities of sulfide [Mensing et al., 1984; Faure et al., 1984], as has the Dufek Complex [Drinkwater et al., 1985], and therefore precipitation of sulfide should not constitute a problem.

The Merensky sulfide minerals are extremely enriched in PGE and gold ($\sim 488 \mu\text{g/g}$). Because the Merensky Reef as a whole contains 8 $\mu\text{g/g}$ PGE and Au and essentially all the PGE are sulfides, the Merensky Reef as a whole only contains some 1.64 wt % sulfide (see Table 1). This quantity could easily be missed during exploration. The PGE content of rocks from the Dufek Complex is generally very low (<10 ppb Pt and <4 ppb Pd), but some Forrestal cumulates have up to 35 ppb Pt and 44 ppb Pd [Ford, 1983]. This may, however, be an indication that the magma has been stripped of PGE by some process as outlined below. Note that similar very low PGE contents occur in most Bushveld Complex rocks [Page et al., 1982] which have yielded significant PGE deposits.

The PGE and Au contents of mantle-derived magmas are low, and an efficient mechanism to concentrate them into a mineable ore body is therefore required. For a Merensky-type deposit it is necessary that two processes occur: (1) an abrupt mixing event in which there is a hiatus in the crystallization and (2) exsolution and deposition of a small amount of PGE-rich sulfides within a short crystallization interval, preferably less than 76 cm (this is the minimum stope width in an efficient mining operation). A PGE enrichment factor of ~ 300 for the ore and 16,000 for the sulfide relative to the magma is required. Note that the amount of sulfides should be relatively low; otherwise a large dilution of the PGE will occur, which would lead to problems in extraction and transport. To produce a mineable ore deposit such as the Merensky Reef, the precipitated sulfides must equilibrate with a large volume of magma. If the magmas are similar to those from the marginal zone of the Bushveld Complex and an ore deposit similar to the Merensky reef is to be produced, then the calculation (see Table 1) shows that a layer of magma between 270 m and 464 m thick needs to be processed with 80% efficiency. These calculations correspond well with the R factor (the mass ratio of magma to immiscible sulfide liquid) approach of Naldrett et al. [1987]. These are relatively small proportions of the total thickness of the layered intrusion and could easily be attained.

The reversal in the Forrestal section of the Dufek Complex (Figure 5) occurs some 700 m below the granophyric roof. This thickness of magma could produce a significant PGE deposit provided the new influx was abrupt, as was the case with the Merensky Reef, and not drawn out, as was the case with the pyroxenite marker.

The compositional variation of the plagioclase and pyroxene near the base of the Dufek Massif section indicates that the composition of the magma was rapidly changing, as is the case near the base of the main zone of the Bushveld Complex (Figure 5). This may indicate that a major influx of magma occurred close to the base of the Dufek Massif section.

The hidden section of the Dufek Complex covered by the Sallee Snowfield may have another major or several minor compositional reversals, as the amount of differentiation shown by the orthopyroxene between the top of the Dufek Massif and the base of the Forrestal Range (5 mol % in ~ 3000 m) is not consistent with the rapid rate of change shown in either the Dufek Massif section (7 mol % in 1000 m) or the Forrestal Range section (8 mol % in 700 m). A similar argument holds for the plagioclase compositional variation (Figure 5). These considerations indicate that there are several stratigraphic positions in the Dufek Complex where a Merensky-type platinum deposit may be located.

The sulfide and PGE mineralogy of the Merensky Reef is laterally quite variable. Such variations may be

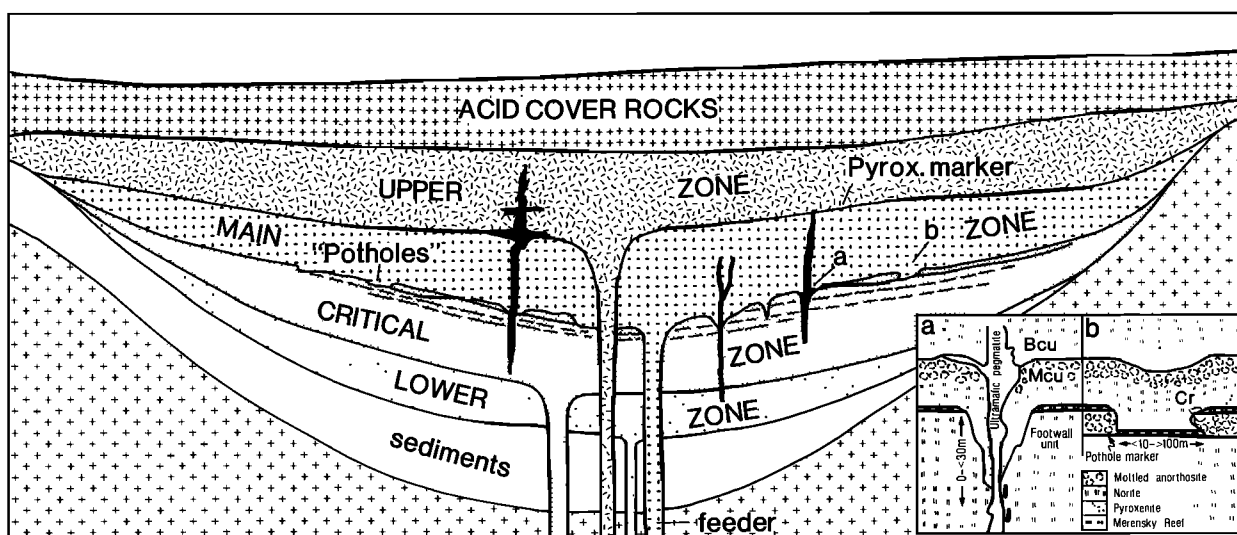


Fig. 9. Schematic cross section of a layered intrusion showing the positions of major magma influxes. The Merensky Reef position is indicated showing the development of a disconformity and the presence of "potholes" and crosscutting ultramafic pegmatites. The inset shows a cross section of the two main types of potholes. The Merensky Reef follows the disconformity and can therefore be severely disturbed. A high ultramafic pegmatite density invariably coincides with a high pothole density, suggesting a common "fluid streaming" origin. These iron-rich pegmatites allow magnetic methods to be used to locate and avoid "disturbed" areas.

primary, such as the proximity to feeders leading to the production of higher temperatures or different fO_2 conditions [Kinloch, 1982], or as a result of secondary processes related to fluid streaming from below [Kruger and Marsh, 1985; Stumpfl and Ballhaus, 1986]. This latter idea is supported by the peculiar mineralogy and composition of the Merensky pegmatoid which contains a bewildering variety of PGE, Ni, Cu sulfides, bismuthides, tellurides, antimonides, etc., as well as Pt-Fe alloys [see Vermaak and Hendriks, 1976].

Large and small crosscutting Fe-rich ultramafic pegmatites are common in the Bushveld Complex and appear to be related to domes in the floor rocks [Reichardt, 1987]. These domes may possibly have acted as traps to focus upward moving fluids expelled from the floor rocks which then disrupted and invaded the newly consolidated crystal pile. These high-temperature fluids are considered to be water rich and Cl rich [Schiffries, 1982; Cameron and Desborough, 1964]. Some of the pipes are richly mineralized (up to 2000 g/t; e.g., the Mooihoek, Driekop, and mined-out Onverwacht pipes [Wagner, 1929; Willemse, 1969; Von Gruenewaldt, 1979]). However, the PGE mineralogy of the pipes is quite different from that of the Merensky Reef, with a preponderance of Pt-Fe alloys [Tarkian and Stumpfl, 1975].

These pipes are also often associated with extensive development of "potholes" in the footwall of the Merensky Reef. Potholes are probably due to a combination of

fluid streaming during the hiatus in crystallization which occurred during the large magmatic influx responsible for the Merensky Reef [Kruger and Marsh, 1985; Buntin *et al.*, 1985] and the erosion of the crystal pile by the superheated mixed magma [Campbell, 1986]. The potholes predate the Merensky Reef, while the ultramafic pegmatites crosscut the whole stratigraphy and clearly postdate the Merensky Reef (Figure 9). The potholes and pegmatites constitute a problem for mining operations, as the reef may be located at slightly different levels in the stratigraphy (Figure 9) or may be entirely lost. The pegmatites alter and change the reef, making it unamenable to processing and PGE extraction.

Conclusion

In this review the Merensky type of deposit has been considered in detail, as this is the most likely type to occur as an economic deposit in the Dufek Complex, and is used as a model in the following economic analysis. Nevertheless, deposits other than the Merensky type or the UG-2 type, such as the Platereef PGE type in the Bushveld Complex where interaction with floor rocks is important, may also be present at the margins of the Dufek Complex [de Wit, 1985]. The Picket Pin (Stillwater Complex) infiltration-type deposit [Boudreau and McCallum, 1986] may also occur but is unlikely to be economic. These deposits and their location within a layered intrusion are schematically illustrated in Figure 9.

TABLE 2. Similarities and Differences Between the Dufek and Bushveld Complexes

Similarities	Differences
Size and thickness	Different magma types/sources (Dufek more Cpx rich; Bushveld more Opx rich)
Multiple magma additions	Dufek has a Proterozoic/Paleozoic basement; Bushveld has Archean basement.
Possibly similar tectonic settings	Dufek probably has no significant chromite.
High initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicating enriched source regions	Magma additions may have been the same for each input in Dufek, not so in the Bushveld Complex.
Similar differentiation histories	No ultramafic section exposed at Dufek
Evidence for scouring and cyclic units	Different age (Dufek—Mesozoic; Bushveld—Proterozoic)

These similarities and differences are listed (subjectively) in order of importance for realizing a potential Merensky Reef-type PGE deposit. From this we estimate a probability of about 75% that such a resource exists.

The main conclusions to be drawn from this brief review are that isotopic, mineralogical, and chemical data are useful stratigraphic markers to locate potential economic mineralization, as well as being tools with which to dissect the Bushveld Complex and other layered intrusions to discover the processes by which they formed and the relative importance and positions of discrete magma influxes. The main similarities and differences between the Bushveld Complex and the Dufek Complex are summarized in Table 2. It is also important to note that both the similarities and differences between the Bushveld and Dufek complexes are quite striking and that an assessment of the actual resources of the Dufek Complex awaits more detailed petrological data. It is not possible at this time to predict with certainty that a PGE deposit in fact does occur anywhere in the Dufek Complex. We estimate the probability of a PGE of the Merensky type to be about 75%, with the chief detracting factors being the differences in magma type (Dufek is Cpx rich and chromite poor) and the unknown factor of the presence of Archean lithosphere. On the other hand, the age of the intrusion does not appear to be an important contributing factor (see Table 2); note that most of the Russian PGE are produced from the geologically young Norilsk intrusion (<120 Ma), and *Buchanan* [1987] lists at least 23 globally distributed mafic layered intrusions of a wide age range that have proven PGE potential.

POTENTIAL RESERVES OF THE DUFEEK COMPLEX: AN ECONOMIC ASSESSMENT

Assuming we will realize a potential opportunity in the Dufek, similar geologic conclusions as formulated in

the above section can be used as a basis on which to evaluate the technical and economic feasibility of a hypothetical Antarctic platinum mine in the Dufek region and thus establish whether any potential PGE deposits should be classified as potential reserves or resources. The essence of such an approach was outlined by *de Wit* [1985]; pertinent points from this study are summarized below; the reader is referred to *de Wit* [1985] for further details.

The possibility of developing such a hard-rock mining venture in the Dufek area of the Antarctic mainland (the Dufek Platinum Metals Mine) was largely assessed within a framework of data generated through two decades of mining experience gained in the Canadian and Greenland Arctic. In particular, the Polaris Mine (Little Cornwallis Island, 77°N) was used as a case study for a feasibility analysis of this hypothetical PGE mining operation in the Antarctic. The Polaris Mine was "retailored" for local Antarctic conditions and accessibility. The deposit was imagined to be a Merensky Reef type, located in the hidden sequence, but within 1000 m of the lowermost exposures of the Dufek Complex. A 5-year interval between discovery and production startup was envisaged, with a further 3 year's buildup to full output rates at a milling capacity of 2050 tonnes per day. Terrain and weather analysis, exploration methods, and ore reserves/grades and variations in the quality of the ores were considered in detail, as well as such technical aspects as mine and housing development, ore processing, infrastructure, and transport. Socioeconomic aspects associated with employment in such an isolated environment, such as availability and costs of labor, taxation, and expenditure on environmental protection, were likewise considered and incorporated into economic models. Table 3 summarizes the parameters considered in the analysis. Models (based on a discounted cash flow analysis, with a real discount rate of 10%) for capital expenditure, operating costs, and profitability were constructed using the MECON computer program (R. Spencer, Royal School of Mines, Imperial College, London).

Modeling was conducted with two fundamental questions in mind. First, what order of profitability can be expected given a reasonable set of invariant geological constraints, including ore grade and composition, and how would such profitabilities change with variable geological and economic parameters? Second, what would be the sort of ore grade needed to contemplate establishing a viable mine in the vicinity of the Dufek Complex?

In essence, the results indicated that, given the 1983 platinum prices kept constant over the mine's life span (26 years), this mine might be a viable proposition, although the returns were too small and unattractive for a financial investor to consider the project seriously (Table 4). Nevertheless, given the constraints and as-

TABLE 3. Incorporated Costs for Dufek Platinum Metals Mine, Antarctica

Expenditure	Cost Breakdown
Capital expenditure	
Mine development:	Shaft, hoist, headframe, equipment Transportation to site Underground equipment and rock development Extras and escalation: 20% of above
Concentrator plant and surface facilities:	General (clearing, foundations) Crushing, crushed ore handling: Concentrator: site and building power plant processing plant sledge transportation to ice front (3000 km) transportation to mine site (550 km) Concentrate storage and loading facilities Trucks Extras and escalation: 25% of above
General	Construction ice road, bridge, ramp Pipelines for water, sewage, tailings Town site accommodation, recreation facilities Development services (engineering, legal, management, fees) Extras and escalations: 20% of above Project overhead costs: 6% of mine development and 8% of remainder capital expenditure
Exploration (~\$10 million U.S.)	Drilling (20,000 m) Salt General transportation (1340 flight hours; \$4000/h)
Operational expenditures	Power Mine, mill and surface (labor and supplies) General administration Transportation costs/tonne concentrate: mine to ice front Transportation costs/tonne concentrate: ice front to smelter Smelting charges/tonne concentrate
Working capital	33.3% of operational costs
Total capital investment	~\$200 million constant 1983 U.S. dollars; ~\$500 million, assuming a constant 10% inflation throughout the life of the mine (26 years)

Modified from *de Wit* [1985].

sumptions, platinum might have been profitably mined, and the results were, arguably, encouraging enough to entice an enterprising mining company to scrutinize the technical and economic structure of the Dufek Platinum Metals Mine models more closely.

As intuitively expected, the results confirm that the possible profitability of the hypothetical Dufek Platinum Metals Mine is closely tied to the platinum price. This is clearly amplified by comparing profitabilities of four very different platinum price scenarios (see Table 4). The project turned out to be a much more interesting proposition, for example, if a real price increase of 2% per year for platinum was assumed over the lifetime of the mine. In the 1983 model, delivery of the first sulfide concentrate was to be produced in mid-1988 and shipped, refined, and sold the following year. It is thus interesting, and timely, to see if a real price increase of 2% (judged by most platinum futures experts to be realistic) has indeed materialized and might be further sustained in the future. Table 5 and Figure 10 compare the average PGE prices for 1986, 1987, and early 1988 with those of 1983, which were used in the 1985 study.

Clearly, a detailed analysis and comparison of these prices is not possible; the platinum prices shown in Table 5 are in constant dollar values, and the real increase in platinum prices and the real costs of the mine development/mine operation should be recalculated. In this respect, it is significant to note that the drastic decrease in the oil prices, by some 50% after the 1985 study, would almost certainly have a significant effect on the total capital and operational expenditure of the hypothetical mine; sensitivity analysis indicates that the profitability of the venture should have been almost as significantly affected by this, as by a relatively similar shift in the platinum price [*de Wit*, 1985, Figure 2.11].

To date, it appears that the long-term platinum price path with an average 2% annual increase used in the 1985 study was justified and would sustain a reasonably profitable platinum mining venture in Antarctica. Furthermore, there is no reason to believe that such a price increase will not continue or even rise substantially in the next decade. Most PGE market analysts are extremely confident about an increasing future demand. The main reason for this is the industrial value of PGE (for example, in the environmental protection and energy industries) as opposed to that of gold [*de Wit*, 1985; *Johnson Matthey*, 1987]. Rather than reiterate all that has been said about this "lucrative" future of platinum, we quote below from a newspaper article [*Business Day*, March 28, 1988], summarizing a report of a well-known Johannesburg broker: "Platinum will attract increasing attention in the future as a high-tech metal. Particularly exciting are prospects for fuel cells, for which some offtake is already being experienced. By the late 1990's, fuel cell-related demand may be as much as 1.84 million ounces. Investment demand for platinum is

TABLE 4. Dufek Platinum Metals Mine Profitability Values of Economic Models and Break-Even Grades of Platinum

Economic Model	Price Scenarios	Ore Quality Pd/Pt	Taxed Models	Real IRR, %	Payback Period, years	Break-Even ROM Grade Platinum g/tonne
1	A	0.42		5.5	7.53	4.85
2	A	0.42	yes	3.57	7.53	5.42
3	A	1.6		9.72	5.52	3.98
4	A	1.6	yes	7.49	5.52	4.45
5	B	0.42		11.38	5.63	3.57
6	B	0.42	yes	9.18	5.63	4.10
7	B	1.6		15.35	4.34	3.03
8	B	1.6	yes	12.85	4.34	3.39
9	C	0.42		6.87	6.74	4.94
10	C	0.42	yes	4.84	6.74	5.04
11	C	1.6		11.18	4.98	3.79
12	C	1.6	yes	8.83	4.98	4.14
13	D	0.42		21.73	2.06	2.84
14	D	0.42	yes	16.85	2.06	3.07
15	D	1.6		28.95	1.55	2.33
16	D	1.6	yes	21.63	1.55	2.56

Base case run of the mine (ROM) grade: 3.94 g/tonne platinum. Base case mine dilution: 22.3%. Price scenarios for platinum: (A) \$475/ounce, constant; (B) \$475/ounce + 2% p.a. real increase; (C) \$475/ounce, increased to \$950 two years preproduction followed by a 10% real decrease for 6 years; (D) \$475/ounce, increased to \$1520 two years postproduction followed by a 10% p.a. real decrease for 10 years. Tax structure: Worldbank-type sliding scale [cf. *Palmer*, 1980]. IRR: internal rate of return: 10% is considered a viable venture.

Table modified from *de Wit* [1985].

very new and is being hampered by limited investment products available. However, growth has been exceptional and is likely to increase, particularly in Japan and the US."

Table 5 also clearly indicates the enormous increases in price of the four PGE's osmium, iridium, ruthenium, and, in particular, rhodium since the 1985 study. Although their abundance in the ores are about an order of magnitude less than that of platinum, these price increases must be regarded as significant "sweeteners." The price increase of rhodium, for example, is closely tied to the increase in demand for automobile three-way catalytic converters for pollution control in the Western world. Although this market demand has now leveled off in the United States, the European and other Western markets have only just started to be tapped [*Johnson Matthey*, 1987]: three-way auto catalysts for European cars are expected to be a major factor in the immediate future growth of the metal's demand.

To summarize, it is clear that a potential Merensky Reef-like mineralized layer in the Dufek Complex could be profitably extracted using 1983 polar technology and a reasonable set of economic parameters. In a broad sense, this is compatible with the predictions of *Elliot* [1976]. Additionally, the project as modeled in the 1985 study allows for significant economic optimization, using alternative, developing technology. Some of this is already being tested for polar utilization. For example, recent advances in Hovercraft technology may prove to be a much more cost-effective means of concentrate

transportation in Antarctica (namely, payloads, speed, and efficiency).

There are many criticisms that can and have been leveled at specific aspects incorporated into the eco-

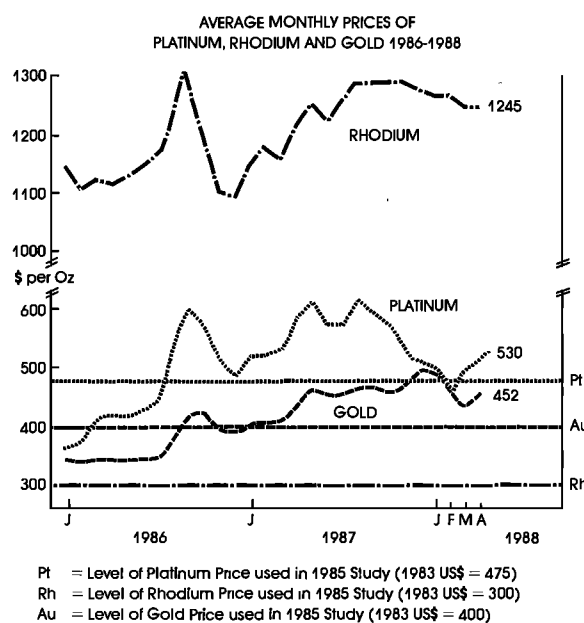


Fig. 10. Platinum, rhodium, and gold price paths 1986 to early 1988, for comparison with the 1983 prices used in the 1985 study. Note the break in scale between platinum and rhodium.

TABLE 5. Typical Dufek Platinum Metals Mine:

PGE	Proportion	Ore Grade, g/tonne	Head Grade, g/tonne	Plant Recovery (78%)	Refining Charges, dollars/g
Platinum	59.2	4.82	3.94	3.07	0.37
Palladium	25.2	1.93–7.70	1.58–6.31	1.23–4.92	0.37
Ruthenium	8.1	0.66	0.54	0.42	1.02
Rhodium	3.0	0.24	0.20	0.16	1.02
Iridium	1.0	0.08	0.07	0.06	1.02
Osmium	0.9	0.07	0.06	0.05	1.02
Gold	3.2	0.26	0.21	0.16	0.08
Total		8.10	6.63	5.17	

Base Metals	Ore Weight, %	Head Weight, %	Refining Charges, dollars/tonne
Copper	0.28	0.23	331.00
Nickel	0.17	9.14	331.00

*All PGE prices quoted in constant U.S. dollars per troy ounce, calculated over the first 8 months (3 months for 1988) of each year indicated; 1 troy ounce = ~31.1 g.

†The price increase from those used in the 1985 model (1983 prices) by 1986/1987.

Sources: *de Wit* [1985], *Johnson Matthey* [1986, 1987], and *British Geological Survey* [1989].

nomic models of this hypothetical Antarctic mine. For example, the working capital used may be too low, even though this is relatively insensitive to the overall profitability of the project [*de Wit*, 1985]. It is also unlikely that the mine and mill would be operated on the basis of one shift per day, especially given the mine's remote and inclement circumstances. Additionally, as was mentioned, the exploration period allowed for is short, and consequently the 5–10 million U.S. dollars (1983 dollars) set aside for this is a minimum estimate. Even within a relatively predictable layered environment, as in the Dufek Complex, perhaps 5 years or more would be required to proceed rationally through the sequential information-gathering exploration, delineation, test work, and evaluation stages. On the other hand, the 1985 model incorporated the requirement for a (very expensive) 1000-m shaft (Table 3). If the deposit is shallow, relatively flat lying with the strike dimensions as the geology suggests, this capital expenditure would not be necessary.

More importantly, however, the exercise here is one of evaluating the economics of developing a mine and identifying potential reserves, rather than that of exploring for a potential opportunity. From all the above it follows that exploration for Merensky-type platinum deposits in the Dufek Complex appears to be an attractive proposition today. Table 4 summarizes the type of ore grades that need to be realized during an exploration program to sustain a reasonably profitable exploitation program thereafter.

However, there are many factors, some beyond pure economic reasoning, that have not been taken into

account in the above analysis. They have been commented on at length in the 1985 study and will not be repeated here. However, one deserves mentioning because the PGE markets are essentially a duopoly between the USSR and South Africa (see *de Wit* [1985] for an overview and references therein): South Africa has 88% of the world's known platinum reserves and 83% of the total output; this will likely rise to 93% by 1993 (*Sunday Times*, *Business Times*, Johannesburg, April 3, 1988). Mines in the Bushveld Complex produced 2.35 million ounces of platinum in 1986, 83% of the total world supply of 2.83 million ounces. This earned South Africa about 1.1 billion U.S. dollars (which increased to more than 1.5 billion U.S. dollars in 1987 [*British Geological Survey*, 1989]). Moreover, this revenue was earned from the sale of only 99,700 kg of PGE, whereas the total production figures from the Bushveld Complex were 115,000 kg. Clearly, a significant amount of PGE is stockpiled. Dumping on the markets of such quantities of "cheap" PGE could shelve any planned exploitation of a new important platinum prospect anywhere, on pure economic arguments. Furthermore, the production potential for the Bushveld Complex is enormous and very cost effective in relation to deposits elsewhere, and in particular, in Antarctica; since the 1985 study, six more mines have been developed or are being developed for new production by 1990 (Figure 3). Perhaps this South African wealth is a saving grace for a "pristine" Antarctic environment, unless of course politics intervene. Despite the dire need for platinum, there is also a great global pressure to move away from South Africa's supplies. Could that dilemma force a forgoing

Grade and Revenue Distribution

Price* 1983	Price* 1986	Price* 1987	Price* April 1, 1988	Percent Increase† by 1986	Percent Increase† by 1987
475.00	424.00	564.00	536.00	-11	19
130.00	110.00	134.00	124.00	-15	3
26.00	75.00	75.00	65.00	289	289
300.00	1,160.00	1,210.00	1,245.00	386	403
300.00	400.00	375.00	315.00	133	125
130.00	650.00	650.00	650.00	500	500
400.00	368.00	447.00	450.00		

Price 1983, dollars/tonne	Price 1987, dollars/tonne
1,852.00	2,160.00
7,055.00	22,000.00

of strict environmental exploration-exploitation standards in Antarctica? Beware Montana's example! However, we reemphasize that the capability of South Africa to meet the world's PGE demands for many years to come must also be seen in the light of its increasing isolation from the world's trade and finance markets (namely, commodity sanctions). For example, it is pertinent to note that the application of trade sanctions on South African coal has led to a massive global price war in this commodity on the world market, with South African producers undercutting other producers.

Finally, we would like to emphasize that all the foregoing is informed speculation and will remain a source of speculation until a detailed geoscientific study of an explorative drill hole is done. This may involve the expenditure of ~10 million U.S. dollars, a decision which must now rest with the Antarctic scientific community.

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AN ENGINEERING ECONOMIC EVALUATION OF MINING IN ANTARCTICA: A CASE STUDY OF PLATINUM

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This study focuses on the engineering and economics of mining platinum group metals and gold from the Dufek intrusion in Antarctica. This intrusion is a Jurassic layered mafic intrusion. Except for the Bushveld Complex in South Africa, it is far larger than any other complex of this type. Chromium, copper, and platinum group metals are considered as speculative resources in this intrusion. There is special interest in the platinum group metals. These are expected mainly in the hidden lower portion of the Dufek intrusion. Possible mining activity could take place in this intrusion. Experience from the Arctic gives reason to believe that mining could be conducted in Antarctica. Developments at the Polaris and Lupin mines in northern Canada are examples of successful operations in adverse climates of the type present in Antarctica. However, logistics, thickness of the ice cover, permafrost, and extremely low temperatures create problems for a hypothetical mining operation and impose hazards for transportation. Economic considerations show no reason to believe that in the near future extraction of minerals could be performed profitably under current cost and price regimes. The very high risk associated with the high cost levels makes such a venture very unattractive. However, with increasing commodity prices and a tightening of the market situation a favorable economic environment could develop. In 1991 the Antarctic Treaty will come up for review, and questions about a mineral development regime are of timely importance. The problem of mineral rights acquisition has to be solved before any mining can be legally performed.

INTRODUCTION

This study is partially based on a previous work by Maarten de Wit [*de Wit*, 1985]. On the basis of four price scenarios, each calculated with two variations of ore quality and once with taxes and once without taxes, he developed a total of 16 cases. He concluded that mining could be conducted profitably in the Dufek intrusion. Among other factors, this would mainly depend on platinum ore grades, underground mine dilution, mining methods, total capital and operational expenditures, and the platinum price.

In the present study the author developed a hypothetical mine design. By using the same capital costs and almost equivalent operating costs as de Wit, a base case and cost and price scenarios were developed. These cases were calculated with various discount rates. The engineering requirements were based on Arctic operations, especially the Polaris and Lupin mines in northern Canada.

Results of this study show that no mining will be economically feasible in the near future. However, the technical design parameters show that mining as such could take place, if the assumptions made in this study comply with the real geological situation of the Dufek intrusion.

GEOLOGY OF THE DUFEK INTRUSION

The Dufek intrusion is one of the largest known ultrabasic layered intrusions in the world. *Wilson* [1969] stated that nearly all of the layered mafic intrusion complexes show economically significant deposits of one or more metals.

Behrendt et al. [1980] estimated the area of the Dufek intrusion as exceeding 50,000 km², which makes it comparable in size to the Bushveld Complex. However, only a tiny upper section of the intrusion is exposed. The intrusion is of Middle Jurassic age and is part of the Pensacola Mountains, adjoining the Precambrian East Antarctic Shield. No intrusive center of this 400,000-km³ volume body has been found yet.

Although more than 95% of the body is hidden under snow and ice and thus only a very small data base is available, speculations on possible resources have been made. *Ford* [1983] compared the Dufek intrusion with the Bushveld and other igneous complexes mainly on the concept of "unit regional value" in order to determine the potential of the Dufek intrusion from known resources in better studied equivalent deposits. Questions about such a comparison may immediately be raised. As was pointed out by *Craig* [1979], the Dufek intrusion should only be compared with intrusions of

similar age, according to the principle of "metallogenic epochs." However, given the physical extent of the Dufek intrusion, it seems reasonable to compare it with intrusions of similar size.

By comparison with the economically important Merensky Reef zone of the Bushveld Complex, Ford [1983] and Ford *et al.* [1983] concluded that a possible equivalent stratigraphic position in the Dufek intrusion might exist in the hidden middle or upper part of the basal section. This would give room for speculation on possible occurrences of chromium, copper, nickel, and platinum group metals. Ford [1983] recorded small concentrations of various elements in the Dufek Massif (lower section) and the Forrestal Range (upper section) of the Dufek intrusion (Table 1), but there were no significant occurrences of platinum group minerals.

TABLE 1. Minerals of the Dufek Intrusion

	Cr, ppm	Cu, ppm	Pt, ppb	S, ppm	V, ppm
Dufek Massif	480				460
Forrestal Range		460	25	800	

Page *et al.* [1982] noted that concentrations of platinum group elements in these two sections are similar to those of similar rocks of the Bushveld Complex above the Merensky Reef zone.

MINING DESIGN

Logistics

Existing Arctic mining activities represented the base for the design of the hypothetical mining operation at the Dufek Platinum Mine (DPM). The following major characteristics such as harsh climatic environment, thickness of the ice cover, permafrost, and extremely low temperatures played an important role in the design. Logistics and transportation are especially affected by these parameters. All building, mining equipment, concentrate, and personnel transportation will be performed by a combined helicopter and heavy cargo plane system. The concentrate will be flown by helicopter to a nearby airstrip which is suited for heavy cargo planes. The possibility of such airstrips was investigated and determined previously [Kovacs and Abele, 1974]. Safe flight operation is possible during the austral summer, late December to early February, only. For building the airstrip and roads, sufficient gravel will be available from the development of two access declines into the ore body. The concentrate will be flown to the Weddell Sea coastline at the northern tip of Berkner Island, from where cargo vessels will ship the concentrate to smelter locations. No empty flights will be necessary, since inbound flights will carry necessary supplies to the mine

for the next 9 months of operation. The flight cost per hour is calculated to be \$4000.

During the construction phase the same shipping procedure will be performed in reverse order. The major thrust of the operation then will be the transportation of prefabricated buildings, processing plant, and equipment for mine development and the subsequent mining operation.

According to de Wit [1985], water supply will be ensured by drilling through the ice, tapping seawater 1000 m below the shelf, which will then be pumped to the mine site by means of a heavy-duty pumping unit built by a West German manufacturer.

Power supply will be provided by two diesel generator sets and two backup units. Since medium speed (600 rpm) MAK diesels are operating smoothly at Polaris, it is advised to use the same equipment at DPM. These units are operating with crude oil or natural gas as fuel. Two waste heat recovery systems are installed to recover waste engine heat for water and building heating. Total installed power of 9200 kW is required to meet an expected peak demand of 4150 kW [Leggatt, 1982; Pfeifer and Kovachevich, 1984]. Figure 1 illustrates location and logistics of the DPM.

Geotechnical Assumptions

The assumptions made in this study are based on (1) geological investigations of the Dufek intrusion and (2) experience from mining activities in the Arctic region.

Especially the Polaris mining operation [Giegerich, 1983; Hopkins, 1986; Scales, 1982; Gowan, 1983] in the Northwest Territories in Canada at 77°N latitude and the Lupin gold mine [Sassos, 1986; Canadian Mining Journal, 1982; World Mining Equipment, 1984] located 50 miles (~80 km) south of the Arctic Circle in the Northwest Territories were studied and provided the basic criteria for the design of the DPM mining operation.

Previous investigations noted that "rocks equivalent to those in the Merensky Reef exist within the concealed basal section at no great depth, and since the layering of the complex is slightly tilted upward to the west, such a reef may occur close to the surface somewhere to the west of Cairn Ridge and Hannah Peak" [de Wit, 1985]. According to de Wit [1985], a Merensky-like Reef can be expected to occur between 100 m and 700 m below the lowest known exposure level.

The Dufek Massif is mainly gabbroic in character. For this study it is assumed that a moderately fractured rock with at least 6000 psi uniaxial compression strength is present in frozen condition. The strength of the overlying strata also is assumed to be 6000 psi.

Permafrost conditions are assumed to exist at least down to 1500-ft (~500 m) depth, which would be similar to the Polaris mine in northern Canada. Mean annual temperature at Belgrano Station (about 300 miles (~480

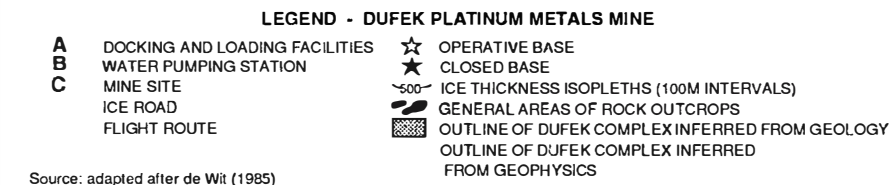


Fig. 1. Location and logistics of the Dufek platinum mine. Adapted after *de Wit* [1985].

km) to the NE) measured over a period of 13 years was -22.2°C . For the stability of the underground openings in the ore zone, the importance of stable permafrost conditions cannot be overemphasized. If the permafrost is allowed to thaw, it will rapidly lose its strength, which will result in extremely hazardous roof stability problems. The ground should remain competent and maintain its strength (and consequently maintain stability of the underground opening) as long as it is kept frozen. At the Polaris mine the average rock temperature is -8°C (-17°F) [Leggatt, 1982]. For DPM it is assumed that the

rock temperature will not increase beyond -10°C at 1500-ft (500 m) depth. Since the moisture content of the rock is assumed to be 5–10%, the permafrost will not lose its strength, and a compressive strength of more than 6000 psi will be sustained. The relatively high ice content of the ore makes it important to keep temperature in the mine well below freezing point, which determines the main design criteria for mine ventilation, drilling, and production.

Furthermore, it is assumed that a bedded deposit with limited variation in thickness does exist. On the basis of

conclusions by *de Wit* [1985], who estimated shallow dips of the layers between 0° and 8° to the southeast, it is assumed that the ore body dips not more than 10° . This assures that underground mining will be possible for at least 20 km into the complex over a strike length of possibly 50 km and allows for the design of a relatively simple mining method. Ore thickness is assumed to be 10 ft (~ 3 m). Since it is an intrusive rock and not in flow, we assume a low silica content in the rock, which together with the relatively low rock strength allows one to assume acceptable operational conditions for milling-type production mining equipment.

Development

Open pit mining for this venture has to be eliminated as an alternative for two reasons. First, the depth of the ore body would require the removal of vast quantities of rock before reaching the ore zone, resulting in a highly uneconomical stripping ratio. Second, the harsh climate would present exceptionally difficult operational conditions for equipment as well as personnel. Additionally, slope stability problems due to expected creep in frozen ground are very likely. These concerns then lead to the conclusion for developing an underground operation.

A twin decline system as access to the ore body is chosen because of the assumed gently dipping ore deposit. One decline will serve for ore haulage by means of a belt conveyor transportation system, while the parallel decline provides for transportation of men, materials, and equipment by mobile methods. Both main entries will be driven into the mineralized zone providing quick ore production for the milling operation. This immediate ore production also provides early bulk samples for metallurgical testing. Stability of the declines driven into the mineralized zone will be the same as driving the main entries into the footwall or hanging wall, as the ore and host rock conditions are very similar.

The cross section of the declines will be $16\text{ ft} \times 10\text{ ft}$ ($5.25 \times 3\text{ m}$), being separated by $44\text{ ft} \times 60\text{ ft}$ ($14.5 \times 20\text{ m}$) pillars. Developing the two declines simultaneously will ensure continuous ventilation. During the first stage the declines will be driven down to the 1200-ft (395 m) level. At the 350-ft (115 m) level, two headings will be driven along the strike as secondary headings. The cross section of the secondary headings is $10\text{ ft} \times 10\text{ ft}$ ($3 \times 3\text{ m}$). Pillar width between secondary headings is also 10 ft (3 m). Four stopings per block will be operated at the same time. Block size will be $312.5\text{ ft} \times 250\text{ ft}$ ($102.5 \times 82\text{ m}$) with barrier pillars of 15-ft (5 m) width. The individual pillar size per block is calculated by assuming (1) 6000-psi rock strength, (2) load increase of 1 psi per foot, and (3) an 80% extraction ratio.

The room width is $31\text{ ft} \times 31\text{ ft}$ ($10 \times 10\text{ m}$) in the

panel at this level. Figure 2 illustrates the general development plan of the mine. Down to a depth of 500 ft (164 m) the load on the pillar is assumed to be 2500 psi. The total area of stope is assumed to be $312.5\text{ ft} \times 250\text{ ft}$ ($102.5 \times 82\text{ m}$) with $18.5\text{ ft} \times 18.5\text{ ft}$ ($6 \times 6\text{ m}$) pillars leading to an extraction ratio of 79.8%. This extraction ratio then changes with depth. Down to a depth of 1000 ft (330 m) the load on the pillar increases to 3333 psi. Therefore the pillar size will increase to $26.5\text{ ft} \times 26.5\text{ ft}$ ($8.7 \times 8.7\text{ m}$), thus decreasing the extraction ratio to 69.6%.

Roof support will be by 6-ft (2 m) splitsets arranged in a $4\text{ ft} \times 4\text{ ft}$ ($1.2 \times 1.2\text{ m}$) pattern. Wire mesh and steel straps will be used additionally in case of a highly fractured roof. Roof bolting jumbos, which combine the functions of drilling the designed hole and inserting the rockbolts, will be used for this operation. However, these machines do require very intensive maintenance.

The proposed mining concept involves the recovery of pillars and backfill of material. Stability of the backfill material is therefore of great concern. Structural design criteria of the backfill material involve its free-standing capacity of at least 10 ft (3 m), and it must not thaw the pillars adjacent to the stope being filled. Thus the thermal equilibrium should be kept stable. During normal operational practice the backfill material will be cooler than the surrounding rock, since frozen tailings will be used. The backfill material will be transported through raise bored holes 6 ft (1.8 m) in diameter. Robbins 73R MAC raise borers will be used. The tailings will be stored on the surface until they are partially frozen. A two-stage dewatering process will be used. The first dewatering operation is performed by means of a hydrocyclone that reduces the moisture to 10–15%. A second stage of dewatering, if needed, will be done by a centrifuge that further decreases the moisture to 5%. For the stopes deeper than 500 ft (164 m), a mechanical backfilling system will be installed. The backfill will be transported into the mined out block through the conveyor decline and the upper level secondary heading, while the ore is hauled through the lower level secondary headings. The mineral processing plant will be a direct flotation system.

Heat balance and arrangement for ventilation are of utmost importance in order to provide for stability of the development. Deterioration of pillars due to changes in heat input have to be avoided. The critical heat sources are (1) natural heat increase during summer months, (2) condensation and freezing of atmospheric moisture, (3) heat generated by combustion engines and consumption of electrical power, and (4) condensation and freezing of water vapor generated by combustion engines.

Keeping the underground frozen is a must in order to not destroy permafrost and sustain rock stability. Thus intake air will not be heated. Additionally, a refrigera-

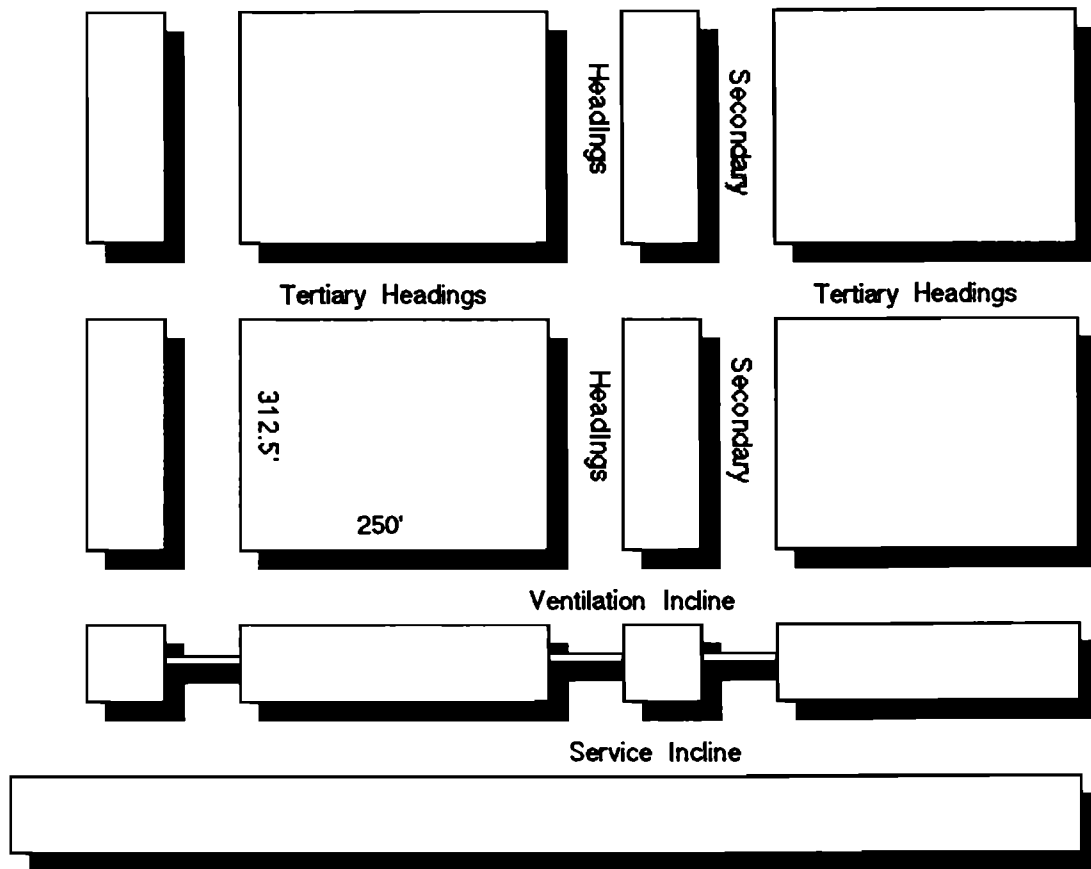


Fig. 2. Development plan of the Dufek platinum mine.

tion unit may be installed to prevent the temperature from rising above -15°C during summer.

Ventilation will be done by drawing air down the service decline at a total rate of 150,000 cfm. The return will be done through the haulage decline. The large volume of ventilation is an important part of keeping the mine cold: by carrying off moisture and the generated heat from equipment operation. Two 48-in.-diameter (1.2 m) axial fans with adjustable blade angles will be used. Additional auxiliary fans will be installed in the individual panels as needed.

Production

The rock at the mine site is assumed to be relatively weak and fractured with a low silica content. This allows for the utilization of roadheaders for all excavation. Productivity is directly related to the energy applied to the cutter head. The "point attack" approach of this machinery concentrates the total power of the cutter head and the weight of the machine on one single cutter bit; thus power requirements for this approach are less than those for a continuous miner. Less wear on

the cutter bits is anticipated owing to low silica content in the ore. Additionally, the self-carrying capacity of the roof is not reduced or destroyed by overbreak due to blasting. Therefore it is possible to obtain a wider support spacing than in a conventional drilling and blasting approach. Drilling and blasting would unfavorably influence roof and pillar stability. Roadheaders have the distinct advantage of mechanizing the cutting and loading of solid rock of a compressive strength of up to 18,000 psi. Hard rock can be mined in many different configurations, achieving a high grade of flexibility and accuracy. With the recommended approach, full mechanization of cutting and loading is possible. Overbreaking and shattering of roof and support rock are avoided by elimination of drilling and blasting techniques. Thus the competency of the rock is enhanced by this technology and the opening is stabilized. Also, rapid advance rates of 55 tons per hour in combination with reducing delays in the drill, blast, and ventilation cycle contribute to the high effectiveness of these machines.

Haulage of the ore will be by a combination of load haul dump (LHD) units and a conveyor system. Roof-

bolted wire rope belt conveyors provide high mobility as they are easily extended, retracted, dismantled, moved, and reassembled. Low capital cost, due to the elimination of heavy structural support and easy accessibility and maintenance, contributes to the system's superiority over a rail system. The simplicity of operation is a major criterion for a continuous transportation mechanism from face to surface. A total conveyor length of 4000 ft (1312 m) will be installed. The assumed 10° incline can easily be handled by belt conveyors. The LHD fleet will transport the mined ore from the roadheaders in the panels to the conveyor system in the lower secondary headings, from where it is transported to the processing plant on the surface.

The entire LHD fleet will be equipped with exhaust scrubbers, low-emission diesel engines, and heated cabs.

All development and production drilling will be by dry drilling equipment with dust collectors. Small mobile compressors will be used for airflushing with dry drilling. In order to reduce ventilation requirements, all production drilling and roof bolting will be done by electric-hydraulic machines. Advance of production will be 20 ft (7 m) per day, producing 35 tons of rock per hour per roadheader. Four roadheaders will be operated simultaneously. If extremely hard rock is encountered, regular ammonium nitrate and fuel oil (ANFO) will be used for a drilling and blasting operation. In this case, a simple rectangular drill pattern is designed producing 2 tons/ft per blast. In this case a 12-in. × 48-in. mobile crusher with a 5-in. setting will be installed. It is assumed that the roadheaders reduce the rock to -5 in. (-0.13 m), and therefore no stationary underground crushing chamber will be designed. Any oversized material will be reduced in the mobile crusher. All drilling equipment will be treated with sodium chloride brine solution to protect it from brittleness. Extensive flushing then is needed to protect it from corrosion. Tables 2 and 3 summarize tonnage of production and the production schedule for the hypothetical mining operation analyzed in this paper.

TABLE 2. Tonnage of Production of Hypothetical Dufek Mine

Production Parameter	Amount
Total production of rock, tons/yr	817,600
Total production per day, tons	2,240
Total production per roadheader, tons/day	550
Total concentrate production, tons/day	300

Production amounts are based on 365 days per year of production, with two 8-hour shifts per day.

TABLE 3. Production Schedule of Hypothetical Dufek Mine

Period	Development or Activity
First year (November-January)	Development of two declines to 1200-ft (~395 m) depth. Construction of airstrip for heavy cargo planes. Surface facilities and infrastructure for accommodation (prefabricated structures).
Second year (November-January)	Construction of surface mill facilities. Construction of power plant. Underground development.
Third year	Production start-up. Development of shipping facilities of the concentrate at the coast. Construction of prefabricated warehouse for storage of 12 months' concentrate. Production, processing plant, and metallurgical testing.
Fourth year	Underground development continued. Beginning of full production.
Fifth year	First shipment of concentrates.

ECONOMIC EVALUATION

General Economic Setting

The economics of Antarctic minerals and their exploitation are a function of the differential in the costs of discovery, production, transportation, marketing, organization, and money [Pontecorvo, 1982]. Parameters that influence these differentials are mainly environmental conditions, distances between supply sources and markets, nonexistent infrastructure and labor supply, special costs for discovery and evaluation, special managerial costs for control and supervision, and the high level of risk.

Capital and operating costs will be distinctly higher in this environment than in other mining areas such as South Africa. Elliot [1977] concluded that production costs for a platinum mine at the Dufek Massif would be 2.9 times as much as buying the commodity on the open market. Thus a more than incremental advancement in mining, processing, and transportation technology is needed to make extraction economical. Potter [1969] determined that probably the highest barrier to commercial operations on the Antarctic shore will be the large

overhead pertaining to icebreakers, equipment and labor in establishing a beachhead, and preparing and maintaining airfields.

When compared with Antarctica, Greenland has substantial mineral resources even though little mining has occurred to date because of unfavorable economics. This is significant because Greenland has less severe climatic conditions, already existing port facilities, proximity to European and American markets, and an indigenous labor force.

In order to forecast at what time in the future Antarctic minerals will be profitable we need to determine with the highest possible accuracy the physical nature of the resource base, production costs, changes in world supply, demand, real price changes over time, trends in technology development and new discoveries, and a multitude of other factors such as international mineral rights.

For there to be economical extraction of Antarctic minerals requires the discovery of either a large-volume ore body or a highly concentrated high-value commodity in sufficient quantity. Ignoring other factors, *Brobst and Pratt* [1973] projected that for minerals currently identified in Antarctica, world reserves lasting for at least 50 more years exist in other regions of the world. For the hypothetical mining operation analyzed here, an ore body containing platinum and associated metals is hypothesized.

Risks of Development in Antarctica

The major risks in developing a mine in Antarctica with the characteristics hypothesized here are obtaining a sufficient and timely supply of capital and obtaining an adequate return on that investment in the future market situation.

Financing at Polaris was based on a Canadian \$180,000,000 credit facility offering a 15-year general corporate obligation. Canadian \$110,000,000 were capital costs with Canadian \$30,000,000 for overruns. Canadian \$40,000,000 of working capital was also supplied [*Giegerich*, 1983]. In order to reduce debt, the Lupin mine operation sold forward a third of 1983's production. Shares were sold at Canadian \$5.60 per share. Financing of net earnings was accomplished by assuming gold price and production [*World Mining Equipment*, 1984]. In both of these mining ventures, financial arrangements were granted to well-established and financially sound companies.

Neither of these Canadian operations, however, faced the extremely risky situation of missing ownership rights, which is the case in Antarctica. Given the lack of tenure over the deposits in Antarctica, no financial institution would be willing to provide the necessary funds for such an operation. Additionally, other risks are of great importance to commercial lenders.

Cameron and Pollio [1987] identified five risks that commercial lenders are most aware of: equity risk, completion risk, operating risk, market risk, and supply risk. Equity risk (the possibility that the project might not generate satisfactory returns) and completion risk (the sponsor's capabilities to meet the stipulations of the financing agreement verified by meeting of completion tests) are assumed by the sponsor. Operating risk (mainly technical factors that affect operations), market risk (that the actual market price is less than the cash flow analysis assumed), and supply risk (the increasing cost for material input) are assumed by the commercial lender once completion tests are satisfactorily fulfilled.

However, two basic elements are closely evaluated by the lender: first, the operator's ability to contain costs within the specifications of the loan contract and, second, the likely price trends throughout the term of the loan. Two independent ways are used by lenders to evaluate a project: evaluation in terms of unchanged real prices, meaning corrected for assumed rates of world inflation, and in current prices. Current prices are used to evaluate the deal, while constant prices are used to evaluate the mine. Predicted price spikes by the sponsor are frequently not fully supported by commercial lenders. Instead, a more conservative approach is followed by commercial money institutions.

It will be seen that for the DPM to be economical, projected price spikes accompanied by a tightening of the supply side of the existing market will be necessary. Under these premises it is obvious that an extremely high risk investment results. In response, the operator would most likely have to finance the project by 100% equity. Even though a promising market development for platinum group metals can be assumed, it is obvious that no forecasting, especially for 30 years into the future under these specific conditions, can be expected to be 100% correct. Short-term fluctuations of supply and demand and prices will always occur.

A situation similar to the one at Polaris concerning the concurrence of shipping season of the concentrate and current market situation will require a proper marketing strategy. Such a strategy will have to solve the problem of possible reluctance of smelters to accept a full year's production within a period of a few weeks owing to the short shipping season. This will necessitate a large working capital due to delayed payment especially with respect to the uncertainty of what market prices will be when the concentrates are delivered and paid for. The short shipping season thus means that part of the inventory costs of the smelters have to be carried by DPM.

Cost and Production Structure

This study follows in its general cost structure the assumptions of *de Wit* [1985]. Tables 4 and 5 illustrate

TABLE 4. Cost Structure of Dufek Platinum Mine

Capital Expenditure (CAPEX)	1983 U.S. Dollars, Millions
<i>Mine Development</i>	
Shaft, hoist, headframe, equipment	11.5
Transportation to site: 30% of shaft, etc., CAPEX	3.5
Underground equipment and rock development	25.34
Extras and escalation: 20% of above	
<i>Concentrator Plant and Surface Facilities</i>	
General (clearing, foundations)	21.95
Crushing, crushed ore handling	4.54
Concentrator	
Site and building	8.075
Power plant	8.075
Processing plant	8.075
Sledge	0.775
Transportation to ice front (3000 km)	0.825
Transportation to mine site (550 km)	0.125
Concentrate storage and loading facilities	10.575
Trucks (\$350,000/50-tonne truck)	3.15
Extras and escalation: 25% of above	
<i>General</i>	
Construction ice road (\$716/km) bridge, ramp	0.394
Pipelines for water, sewage, tailings (\$115.90/km)	0.356
Town site accommodation, recreation facilities	14.988
Development services (engineering, legal, management, fees)	15.525
Extras and escalation: 20% of above	
Project overhead costs: 6% of mine development and 8% of remainder capital expenditure	
<i>Exploration</i>	
Drilling (20,000 m)	3.00
Salt (\$200/tonne; 0.04 tonne/m drilled)	0.16
General transportation (1340 flight hours; \$4000/h)	5.36
Operational Expenditures (OPEX)	1983 U.S. Dollars, per Day
Power	6,714.00
Mine labor	10,493.00
Mine supplies	12,138.00
Mill labor	4,373.00
Mill supplies	6,483.00
Surface labor	10,045.00
Surface supplies	2,383.00
General administration	17,707.00
Transportation costs/tonne concentrate: mine to ice front	73.15
Transportation costs/tonne concentrate: ice front to smelter	68.75
Smelting charges/tonne concentrate	76.88

From *de Wit* [1985]. Working capital is 33.3% of operational costs.

his calculated capital and operational expenditures for a similar venture. Tables 6 and 7 show variations to his cost figures derived from the underlying data for this study.

Equipment costs are calculated according to the engineering considerations described by the mine design. The costs used here can be compared and contrasted with those of *de Wit*. Total capital costs are the same. The operational costs in this study are slightly less than

de Wit's owing to a lesser working capital requirement. There is also a difference in transportation, but the different transportation scheme used here does not increase costs. *De Wit's* calculations already include costs for air transport facilities. It can be shown that the hazardous truck transportation of the concentrate over his proposed ice road can be replaced economically by air transportation. The capital costs for the ice road construction and its maintenance and investment in an

TABLE 5. Total Investment of Dufek Platinum Mine

	Millions of Dollars	
	Constant 1983 Dollars	Current Dollars
Exploration, capital costs	8.5	9.8
Shaft and equipment capital costs	17.9	28.0
Underground mining capital costs	30.4	47.9
Treatment plant capital costs	73.9	115.6
General facilities capital costs	50.9	79.6
Project overhead costs	12.3	19.2
Total capital costs	193.9	300.1
Working capital	9.8	188.3
Total investment	203.9	488.4

From *de Wit* [1985].

ice sledge and trucks for transportation plus the associated operational costs of \$17,500,000 open the alternative of air transportation of the concentrate. By comparing these figures with air transportation costs of \$4000 per flight hour, it appears that transportation of the concentrate by air becomes feasible.

The production figures and parameters in Table 8 are based on the previously described engineering design and geological data from the Bushveld Complex.

Ore distributions of the individual platinum group metals and gold were chosen similar to the Merensky

TABLE 7. Comparison of Transportation Costs of Concentrate to Ice Front

	Value
Concentrate production per day, tons	300
Days of operation of concentrator per year	365
Payload capacity of Hercules LC-130, tons	20
Total flight hours required per year	5,475
Costs per flight hour, dollars	4,000
Total costs for transportation of concentrate by air, dollars	21,900,000
Operational cost for transportation by ice road, dollars	17,500,000*
Costs for building ice road, dollars	394,000*
Costs for trucks, dollars	3,150,000*
Costs for buying sledge, dollars	775,000*
Total cost for transportation of concentrate by ice road, dollars	21,819,000

*Derived from *de Wit* [1985].

Reef. The ore composition of the platinum group metals and gold are as follows: platinum, 59.5%; palladium, 25.7%; rhodium, 3.7%; ruthenium, 6.4%; iridium, 1.0%; osmium, 0.1%; and gold, 3.6%. Prices per troy ounce for the individual ores were assumed to be as follows: platinum, \$600; palladium, \$150; rhodium, \$1300; ruthenium, \$80; iridium, \$600; osmium, \$700; and gold, \$400.

Evaluation Methods

Mining operations are commonly evaluated by determining a minimum rate of return that the project should yield or by calculating the earliest possible payback period. Discounted cash flow methods are techniques to arrive at this objective.

Usual methods for determining the profitability of a mining operation by applying discounted cash flow include net present value, internal rate of return, payback period, and present value ratio. These different methods should be analyzed together, since various

TABLE 6. Equipment Costs According to Mine Design

Number	Equipment	Dollars per Unit
4	Roadheader (80,000 lb, 305 hp)	567,632
4	LHD (8 yd ³ , 231 hp)	229,510
1	Electric-hydraulic drill jumbo	240,000
	Conveyor belt (4000 ft, 24 in. wide, 1600 tph)	278,611
1	Compressor (350 cfm, 100 psi, 75 hp)	23,000
2	Fan (48-in. fan diameter, 6-in. static pressure)	39,323
1	Jaw crusher (12 × 48, 5-in. setting, 180 tph)	67,465
1	Raise boring machine (6.6–8.8 ft diameter, 1969 ft)	936,000
1	Scissor lift truck	63,440
1	Lubrication truck	75,920
1	ANFO truck	71,760
1	Crane	40,000
2	Personnel carrier (12 persons)	61,360
1	Mechanical scaler	56,160
2	Rock bolter	225,000
1	Diesel land cruiser	60,000
3	Building (60 ft × 100 ft (20 m × 33 m))	87,472
1	Pump (water supply)	500,000
1	Refrigeration unit	1,500,000

Derived from *Western Mine Engineering* [1984].

TABLE 8. Parameters for Production Calculation

	Value
Production per roadheader, tons/h	35
Number of roadheaders in operation	4
Hours of operation per day	16
Total tons of production of ore per day	2,240
Ore grade of PGM and gold, g/ton	8.1
Dilution, %	20
Mill recovery, %	85
Refinery recovery, %	98
Total recovery of PGM and gold, g/day	12,091
Total days of production per year	365
Total production of PGM and gold per year, troy oz (1 troy oz = 31.1 g)	141,985

PGM, platinum group metals.

aspects of the investment are measured with different methods.

The discount rate can be determined as the cost of capital in the sense that it can be used to determine what the use of that capital in other investments might earn. Therefore the discount rate can be set equal to the minimum rate of return of such an investment.

Cash flow is calculated by totaling the revenue of a specific time period, usually 1 year, and subtracting all the expenditures of that time period from it, including taxes and interest payments. Depreciation and depletion allowances reduce the taxable income but add to the cash flow after taxes, thus increasing the total cash flow.

To calculate the net present value (NPV), each positive and negative cash flow is discounted to present value, using the appropriate discount rate. The sum of all present values of these cash flows gives the net present value of the investment opportunity. The net present value is the indicator of the net yield of an investment, by determining the maximum amount that can be paid for an investment and still receive the desired minimum rate of return in its present value. Thus the obtainable objective is a positive net present value.

The present value ratio (PVR) compares the net present value of a project with its initial investment. This method allows one to measure profitability per dollar invested and thus to rank projects in order of profitability. Especially in situations where more investment opportunities than funds are available, calculation of the PVR is a useful decision criterion.

The discounted cash flow rate of return (DCFROR) or internal rate of return (IRR) is the average percentage return that an investment opportunity is expected to yield over its life. This is evaluated by equating the present value of the positive cash flows with the present value of the negative cash flows and then determining that discount rate that produces the equality. The minimum requirement is a rate of return greater than the discount rate.

The payback period is the number of years required to recover the original investment plus working capital at a 0% interest rate.

Scenarios

This study will focus on NPV, PVR, IRR, and payback period. The original base case and three alternative scenarios form a sensitivity analysis. The base case adheres strictly to average figures and production rates common in platinum operations. It will be seen that the base case is quite uneconomical. Those parameters that are most speculative were then changed and incorporated into the scenario to determine what conditions need to be present to make the project economical. These variations represent the following combinations

of factors that influence the final evaluation: scenario A, alternative initial investment requirements ranging from 75% down to 5% of the base case values; from these results we can determine the maximum initial investment that guarantees a profitable outcome; scenario B, alternative operating cost requirements ranging from 85% down to 50% of the base case values; from these results we can determine the maximum operating costs that guarantee a profitable outcome; scenario C, determination of prices of the individual commodities that are necessary to guarantee a profitable development of the mine.

In the base case it was assumed that other minerals besides platinum are going to be extracted. This will be at a rate usual for this kind of platinum operation. The production ratios of these commodities and their relationships are calculated according to the distribution ratio in the Merensky Reef of the Bushveld Complex. This distribution is taken into account by assuming the individual production rates of the metals as shown in the various scenarios. The assumed production rate of 141,985 oz (4,415,733.5 g) of platinum group metals and gold is in accordance with the operation in the Stillwater Complex in Montana. However, the distribution between platinum and palladium is reverse in the northern hemisphere. While the Stillwater operation assumes a production ratio of 25,000 oz of platinum to 75,000 oz of palladium, the opposite is usually the case in the southern hemisphere. The Bushveld Complex ratio is about 2.3:1 platinum to palladium. Although the size of the proposed Dufek mining operation is comparable to the Stillwater mine, the geology of the Dufek intrusion is similar to the Bushveld Complex. Therefore the platinum group metal distribution at the Dufek intrusion is similar to the distribution ratio observed at the Bushveld Complex.

Scenario A determines the influence of the initial capital outlay as a major cost factor for cash flow calculations. Since a tremendous initial investment is necessary in order to start operations, it is of utmost importance to determine the sensitivity of the capital costs on the final outcome of the venture.

Scenario B investigates how much the operational costs must decrease for a profitable operation to be possible when holding revenues are fixed. Since operational costs in this harsh environment do have a major impact on the profit-loss situation, it is important to determine their sensitivity.

Scenario C determines how high the required price must go for a profitable operation throughout the mine's lifetime when operational costs are assumed to be fixed. Since price developments are critical for revenue generation, it is important to find lower price limits necessary in order to keep the operation profitable.

Assumptions

In order to evaluate this project, certain assumptions have been made. Assumptions were based on similar operations, past experience, current trends, and the state of technology. Assumptions made are as follows:

1. Mineral and entry rights will be granted and land will be leased.
2. The life of the mining project will be 30 years from the time of initial investment.
3. Financing of the project will be strictly from the company's own equity capital.
4. Salvage value for all plant and equipment will be zero. No additional equipment will be needed, and any upgrading or repair will be funded out of working capital.
5. Land is to be leased, and there will be no salvage value of land.
6. Inflation will be figured at a constant rate of 5%.
7. There will be no escalation of prices.
8. Any changes in the tax system will have insignificant effect on the project.
9. Taxation will be calculated at 28%.
10. Losses will be carried forward.
11. Production will remain constant at 141,985 oz (4,415,733.5 g) per year.
12. Labor, both skilled and unskilled, will be available.
13. By-product recovery (copper and nickel) will be insignificant in the final outcome.
14. Working capital is figured at 25% of total operational costs.
15. Depreciation will be according to accelerated cost recovery system (ACRS).
16. Depletion will be calculated at 14% according to the U.S. tax code.
17. A real discount rate of 10% is assumed.
18. Expenditures for operational costs start in year four, even though operational costs will occur in years zero through three.
19. All capital investment will be done in years zero through three.

RESULTS

The result of the base case scenario makes it immediately obvious that no profitable mining operation can be conducted in the Antarctic under current price and technical conditions. All of the evaluation methods led to negative results. The immense influence of the initial investment on the profitability of this operation is graphically demonstrated in Figure 3. Commonly, an increasing discount rate will result in a lower NPV. However, the base case scenario illustrated a reverse picture: increasing discount rates result in a more favorable NPV. An abnormal NPV profile at discount rates of 0%, 5%, 10%, 15%, and 30% is then the result. This is due to

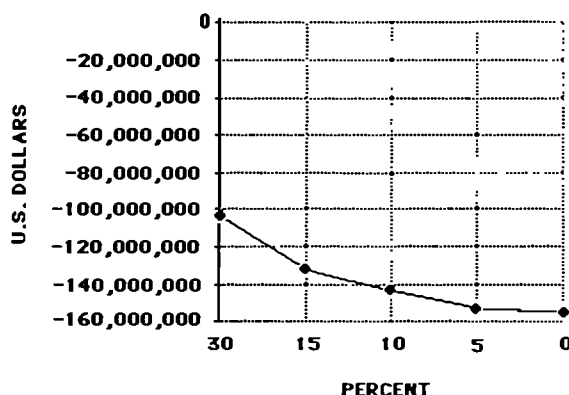


Fig. 3. NPV profile in real percent.

the necessarily very high initial investment in the beginning of the operation, which then is followed by very small positive cash flows throughout the remainder of the lifetime. Figure 4 illustrates this phenomenon graphically at a 10% real discount rate. The choice of the discount rate on the present value of cash flows is clearly much more important in the first few years than in later years. In comparison with tremendously high negative cash flows in the beginning of the project, the discounted positive cash flows become so small that they are not shown graphically after year 15. It has to be pointed out that even though increasing discount rates improve the NPV drastically, the final result will nevertheless remain negative. Therefore it becomes obvious that the IRR is zero. Clearly, the PVR also shows the expected negative result of -0.81 , and no payback period is indicated.

A break-even analysis of the base case scenario was performed to determine the necessary production. Figure 5 shows that a total production of platinum group metals and gold of at least 260,000 oz (8,086,000 g) per year is required to break even. Operating costs per

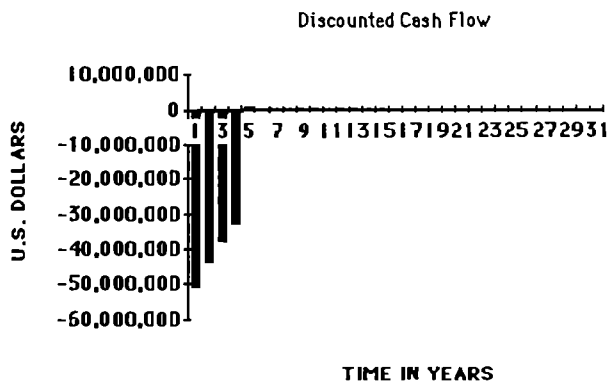


Fig. 4. Discounted cash flows at real 10%.

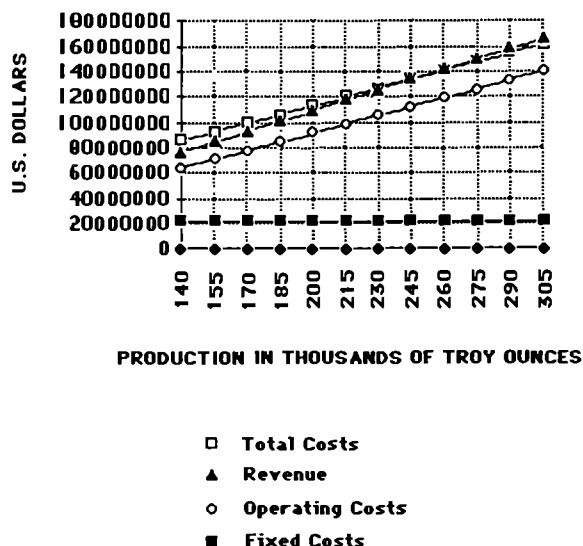


Fig. 5. Break-even analysis.

ounce of production were calculated to be \$460, which happens to be twice the operating costs in the Bushveld Complex. Total fixed costs of \$203,900,000 were converted to an equal annual value (EAV) of \$21,629,556 by applying the capital recovery factor:

$$EAV = PV\{i(1+i)^n / [(1+i)^n - 1]\}$$

where $PV = 203,900,000$, $i = 10\%$, and $n = 30$ years. The average price for the seven individual ores likely to be produced from the Dufek intrusion was calculated to be \$547 per ounce. The break-even analysis shows that the assumptions made in the base case will not provide for a profitable mine development unless a drastic increase of the production rate occurs.

In scenario A it was determined to what extent the initial investment has to decrease in order to make this project an economically viable operation. The results obtained at a real discount rate of 10% are shown in Table 9.

TABLE 9. Effects of a Decrease of Capital Investment on NPV (at a Real Discount Rate of 10%/yr)

NPV	Capital Investment/Year	Percent of Base Case
-143,133,929	50,975,000	100
-105,321,184	38,231,250	75
-67,578,439	25,487,500	50
-29,695,694	12,743,750	25
554,503	2,548,750	5

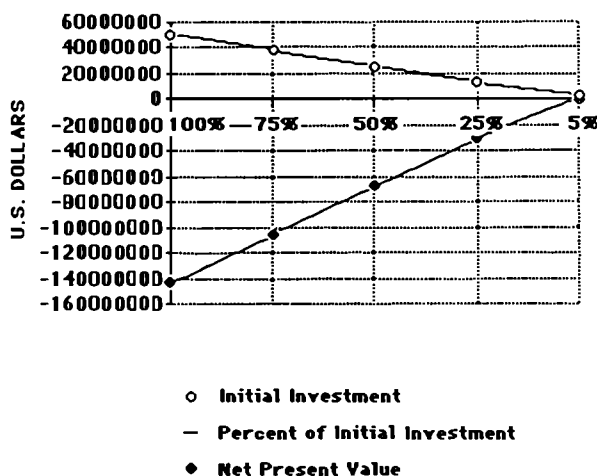


Fig. 6. NPV at real 10% versus initial investment.

The results indicate that at a real discount rate of 10% the initial investment has to decrease by 95% before this operation becomes profitable. This fact by itself indicates already the impossibility of such a venture. Figure 6 illustrates this relationship graphically. At an annual investment of \$2,548,750 for 4 years a positive NPV of \$554,503 will be the result. At decreasing discount rates the NPV is improving as shown in Table 10. The IRR indicates with 10.76% that this operation would be profitable and possibly preferable to other investment opportunities at that discount rate. The PVR of 0.06 is fairly low, and therefore investment in this mine would not be encouraged. This is consistent with the fairly long payback period of 25 years. It has to be emphasized that a decrease in capital costs by 95% is very unlikely to occur.

In scenario B it was determined to what extent the operating costs would have to decrease before a profitable mining operation would be possible. The results obtained at a real discount rate of 10% are shown in Table 11.

Decreasing the operating costs by 50% will lead to a positive NPV. This is graphically shown in Figure 7. By choosing a lower discount rate, increasingly positive NPVs are the result (Table 10). The calculated IRR equals 10.42%, when operating costs are 50% of the base case value. This indicates that investment in this operation could lead to a positive outcome. It also shows that this investment might be preferred over other investment opportunities since the IRR is higher than the chosen discount rate. However, the PVR is fairly low, indicating that profit on a per dollar basis of investment would be very small. This is consistent with the long payback period of 27 years.

The overall result of this scenario shows that investment under these assumptions could be profitable. However, it is very questionable if the operating costs

TABLE 10. Results of Individual Scenarios

	Parameter	Value
<i>Base Case</i>		
Initial investment of 203,900,000 U.S. dollars.	NPV at 30% real discount rate, dollars	-102,885,737
	NPV at 15% real discount rate, dollars	-131,799,309
	NPV at 10% real discount rate, dollars	-143,133,929
	NPV at 5% real discount rate, dollars	-153,220,215
	NPV at 0% real discount rate, dollars	-155,020,564
	IRR, %	<0
	PVR (at NPV 10%), dollars	-0.81
	Payback period, years	...
<i>Scenario A</i>		
Maximum initial investment that guarantees a profitable outcome (or a decrease in the base case by 95%).	NPV at 15% real discount rate, dollars	-2,038,251
	NPV at 10% real discount rate, dollars	554,503
	NPV at 5% real discount rate, dollars	7,062,960
	NPV at 0% real discount rate, dollars	25,248,918
	IRR, %	10.76
	PVR (at NPV 10%), dollars	0.06
	Payback period, years	25
<i>Scenario B</i>		
Maximum operating costs that guarantee a profitable outcome (or a decrease in the operating costs by 50%).	NPV at 15% real discount rate, dollars	-41,681,125
	NPV at 10% real discount rate, dollars	5,758,024
	NPV at 5% real discount rate, dollars	122,932,924
	NPV at 0% real discount rate, dollars	445,896,229
	IRR, %	10.42
	PVR (at NPV 10%), dollars	0.03
	Payback period, years	27
<i>Scenario C</i>		
An increase in commodity prices by 50% while keeping all other factors constant.	NPV at 15% real discount rate, dollars	-37,869,163
	NPV at 10% real discount rate, dollars	12,846,289
	NPV at 5% real discount rate, dollars	137,819,460
	NPV at 0% real discount rate, dollars	482,240,496
	IRR, %	10.92
	PVR (at NPV 10%), dollars	0.07
	Payback period, years	24

can be reduced by 50%. New cost-saving technologies for energy supply, concentration, and transportation need to be developed to achieve cost reduction. Even if these new technologies are developed, they will very likely reduce operating costs by less than 50%. The

likelihood of this scenario happening in the near future is very low.

In scenario C, prices of the individual commodities were raised by 50%, leading to a higher gross revenue, while all other factors remained constant. Figure 8

TABLE 11. Effects of Decrease of Operating Costs on NPV (at a Real Discount Rate of 10%/yr)

NPV	Operating Costs/Year	Percent of Base Case
-143,133,929	65,150,000	100
-93,191,021	55,377,500	85
-61,675,911	48,862,500	75
-36,301,494	42,999,000	66
5,758,024	32,575,000	50

shows a progressively increasing gross revenue over total costs and operating costs. While in the base case scenario the gross revenue barely covered the operating costs, total costs are fully covered in scenario C. At a 10% discount rate a NPV of \$12,846,289 was calculated. This shows clearly that the high initial investment can be compensated for by an increased market value of these commodities. At decreased discount rates this result becomes even more evident, as is shown in Table 10. Figure 8 illustrates that at midpoint of the lifetime of the operation the gross revenue progressively increases more rapidly than the cost components. The resulting cash flows of these later years therefore do have a bigger influence on the positive result of the NPV than in the base case. The IRR of 10.92% indicates a profitable operation under these conditions, which makes this investment even attractive as opposed to other opportunities, since the chosen discount rate is lower. The PVR shows a fairly low profit per dollar (0.07). This is combined with a fairly long payback period of 24 years.

Overall, it does not seem unreasonable that commodity prices could rise to the levels of this scenario.

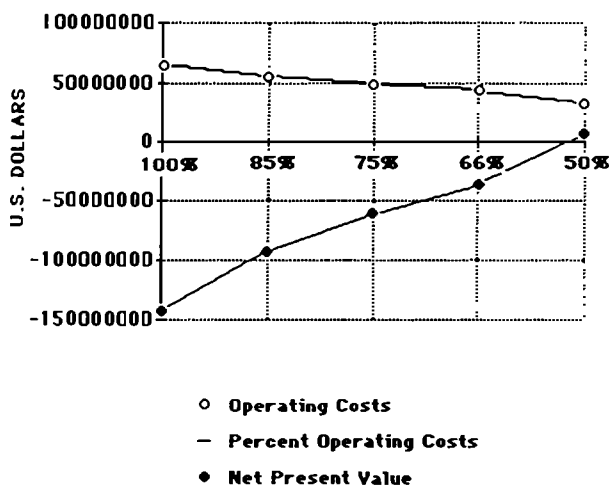


Fig. 7. NPV at real 10% versus operating costs.

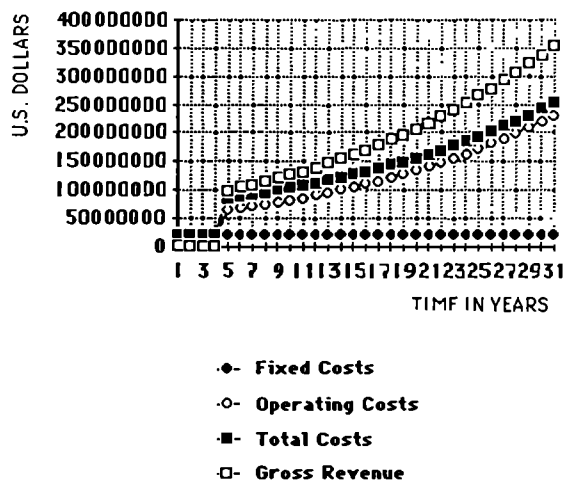


Fig. 8. Gross revenue versus costs.

Platinum prices were once above \$900 per ounce in 1979. Market conditions for the platinum group metals and gold are presently very favorable. This scenario is not out of the range of possible developments in the commodity market. As was shown in the previous scenarios, it seems unlikely that cost-cutting measures will lead to a profitable mining operation in the Antarctic in the near future. However, market developments with upward moving commodity prices do provide a possibility for such a venture. Clearly, even if prices rise according to this scenario, the profit would still remain marginal, considering the high risk that has to be taken.

SUMMARY

At an initial investment of \$203,900,000 and a 10% real discount rate, the base case results in a NPV of -\$143,133,929. The maximum initial investment allowable to record a positive NPV is calculated in scenario A. If capital costs are reduced by 95%, a NPV of \$554,503 at a 10% real discount rate is achieved. If operating costs are lowered by 50% (scenario B), a NPV of \$5,758,024 at a 10% real discount rate is achieved. Scenario C records a NPV of \$12,846,289 by raising the individual commodity prices by 50%, while keeping all other factors unchanged.

No mining will be undertaken in Antarctica in the foreseeable future. This is partly due to a lack of reliable data on the area. Systematic scientific surveys which started about 30 years ago are mainly restricted to ice-free areas. Less than 10% of the exposed rocks have been mapped in detail, and probably less than 1% have been examined for economic minerals [Elliot, 1977]. Informa-

tion on hydrology, soils, and permafrost is very sparse, and thus proper engineering design is very difficult for ice-covered regions. The suggested mining method certainly allows for successful mining in this region under the given assumptions; consequently, proper mining can be performed with today's technology.

Precise data on ecological processes and interaction with the food chain are not available at this point, so that environmental impact statements still do not give a clear picture of possible adverse influences on the environment by mining activities.

The economics are certainly not favorable for any of the minerals found in the Antarctic at this point. Especially high initial investment and operating costs do have a strong negative influence on the profit-loss profile of such a venture. This is clearly shown by the base case and scenarios A and B evaluated here. Scenario C, however, demonstrates that a price increase of 50% can make such an investment profitable. Such a price increase is certainly not unreasonable. There is historical precedent for such a price surge: it happened in 1979–1981. Also precious metals are considered an investment opportunity. This became obvious in the October 1987 stock market crash, when precious metals were used to hedge against plunging stock prices. Precious metals prices remained fairly high and did not follow the general downturn of the stock market. Nevertheless, too many other deposits of much higher reserve potential in other parts of the world will be mined before intensive exploration will be started for Antarctic minerals.

Geopolitical considerations will be closely tied to more reliable data on the resource potential of the Antarctic. Many of the existing gaps, however, will not be filled quickly but will take long-term scientific investigations in order to provide results.

However, the fact that a continent the size of the United States and Mexico combined has been so inadequately explored is alone suggestive that economic deposits will be found there in the future.

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INVESTIGATION OF MINERALIZATION IN THE SOUTH SHETLAND ISLANDS, GERLACHE STRAIT, AND ANVERS ISLAND, NORTHERN ANTARCTIC PENINSULA

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Twenty localities in the South Shetland Islands, the Gerlache Strait, and southern Anvers Island were examined for their potential as sites of "Andean-type" porphyry and related base and precious metal mineralization. Field studies consisted of geologic mapping and sampling for petrographic studies and trace element analysis (Cu, Pb, Zn, Au, Ag, Mo, W). Copper, lead, and zinc are present in most of the localities that were examined, and molybdenum, gold, and silver also may be important components of the mineralization. Four localities have been identified as possible sites of porphyry and related base and precious metal mineralization: (1) east of Palmer Station, southwestern Anvers Island; (2) along the coast north of Bahia Frei in the Gerlache Strait; (3) northeast of False Bay, Livingston Island; and (4) north of Johnsons Dock (Hurd Peninsula), Livingston Island. Additional study will be required to define the resource potential of these localities.

INTRODUCTION

The presence in the Antarctic Peninsula of rocks with broadly similar geologic histories to highly mineralized rocks in the Andes of South America, together with the widespread presence of trace mineralization, has led researchers to suggest that the Antarctic Peninsula may contain significant undiscovered mineral deposits. However, in spite of recent statements concerning the regulated development of the oil and mineral wealth of Antarctica [Denver Post, 1988; New York Times, 1988], it is not likely that metallic and nonmetallic deposits that may be discovered in the Antarctic Peninsula, or anywhere else in Antarctica for that matter, will be commercially exploited in the near future. Logistical constraints because of the climate and the location of the continent make mining of anything but the richest deposits unlikely, and mineral deposits of all sizes and grades await development in more accessible parts of the world (e.g., in the Andes of South America). Small-tonnage, high-grade deposits of materials with a high unit value (e.g., diamonds, platinum group elements, gold, and perhaps silver) are possible targets for exploration and commercial development in Antarctica. Ex-

ploitation of mineral resources for political and territorial purposes, however, remains a possibility any time.

The geologic history of the northern Antarctic Peninsula can be considered largely in terms of (1) the late Paleozoic-early Mesozoic Gondwana plate margin, (2) the mid-Mesozoic to Tertiary "Andean" plate margin, and (3) late Cenozoic rifting. Nearly all of the mineralization in the Antarctic Peninsula is associated with Andean-age plutonic and volcanic rocks.

Gondwana Plate Margin

Rocks formed during the time the Gondwana plate margin was active (late Paleozoic to early Mesozoic) are widely distributed in the region of interest (Figures 1 and 2), and they form the "basement" for younger rock units. The Gondwana assemblage that has been preserved represents portions of the fore-arc and magmatic arc terrains that originally existed along the Pacific margin of Gondwana [Dalziel, 1982], plus perhaps some of the back-arc terrain [Smellie, 1987]. Sedimentary sequences of this age consist predominantly of quartzose greywacke and shale with local but significant limestone, mudstone, siltstone, and conglomerate. They are found in the South Orkney Islands, the South Shetland Islands, the Antarctic Peninsula, and Alexander Island. The strata exhibit polyphase deformation, and structural trends generally are parallel or subparallel to the regional physiographic trend. Minerals typical of blueschist facies metamorphism have been found in rocks from the South Orkney and South Shetland island

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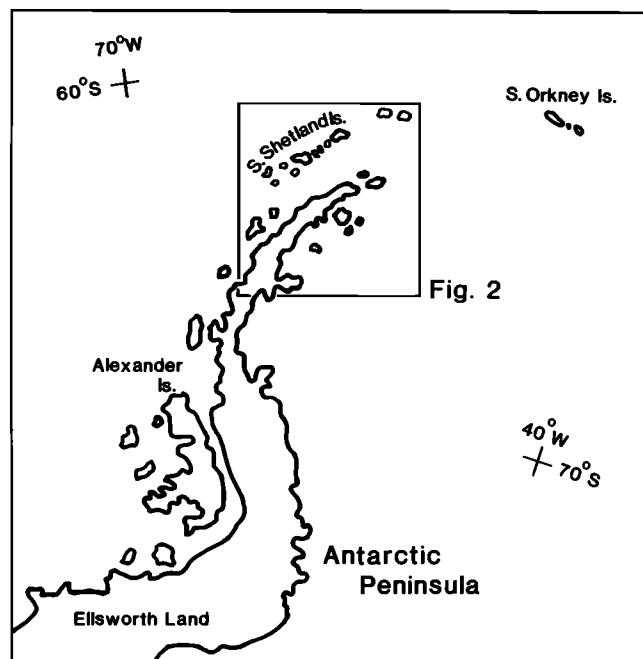


Fig. 1. Northern Antarctic Peninsula. Area of Figure 2 shown.

groups and from Alexander Island, which has led researchers to conclude that the rocks formed at least in part during subduction-related process, although the ages of metamorphism and uplift are not well established and not all of these rocks are necessarily part of the Gondwana plate margin [Smellie, 1981; Dalziel, 1982; Edwards, 1982; Herve *et al.*, 1983; Burns, 1984; Trouw *et al.*, 1987]. Evidence for a Gondwana magmatic arc is very sketchy and exists as a single date (209 m.y.) for a granite on Cole Peninsula, eastern Graham Land [Pankhurst, 1982].

Andean Plate Margin

The pre-Jurassic (Gondwana) basement in the northern Antarctic Peninsula is overlain by clastic and volcanoclastic rocks of late Jurassic to early Tertiary age [Farquharson, 1982, 1983, 1984; Elliot and Gracianin, 1983; Elliot, 1988]. These rocks record the development of block faulting and the initial stages of magmatic activity that postdate development of a sparsely documented but widespread unconformity that separates Gondwana and Andean events [Elliot, 1988]. The volcanic and plutonic rocks that form the backbone of the Antarctic Peninsula (Figure 2) represent the Andean magmatic arc. Mesozoic volcanic sequences range in composition, west to east, from basalt to rhyolite [Weaver *et al.*, 1982], and plutonic rocks with similar compositional ranges and distributions are exposed across the Antarctic Peninsula [Saunders *et al.*, 1982].

Both groups of workers feel that geochemical variations in the rocks are consistent with subduction from the Pacific side of the Antarctic Peninsula.

Rocks of the magmatic arc were emplaced more or less continuously from late Triassic to early Tertiary, with peaks of activity during the early Jurassic (180–160 Ma), early Cretaceous (130–100 Ma), late Cretaceous (100–80 Ma), and early Tertiary (60–50 Ma) [Rex, 1976; Pankhurst, 1982]. These episodes correspond to groupings of dates described by Saunders *et al.* [1982], who placed the peak episode of plutonic activity between 110 and 90 Ma. Volcanism was active in the arc throughout much of the time of plutonism [Birkenmajer *et al.*, 1982a, b, 1986a, b; Pankhurst, 1982; Thomson and Pankhurst, 1983; Barbieri *et al.*, 1987]. The presence of airfall deposits and volcanic detritus in adjacent back-arc and fore-arc basins suggests that Andean magmatism began as early as mid-Jurassic in eastern Ellsworth Land [Quilty, 1977], had spread throughout the Antarctic Peninsula by latest Jurassic time, and continued until the mid-Tertiary [Elliot, 1983, 1988]. In the northern part of the Antarctic Peninsula, the focus of magmatic activity migrated generally from east to west, and from south to north with time [Pankhurst, 1982; Saunders *et al.*, 1982; Weaver *et al.*, 1982; Thomson *et al.*, 1983; Storey and Garrett, 1985].

Late Cenozoic Events

The geologic record of the late Cenozoic in the northern Antarctic Peninsula is meager but, in general,

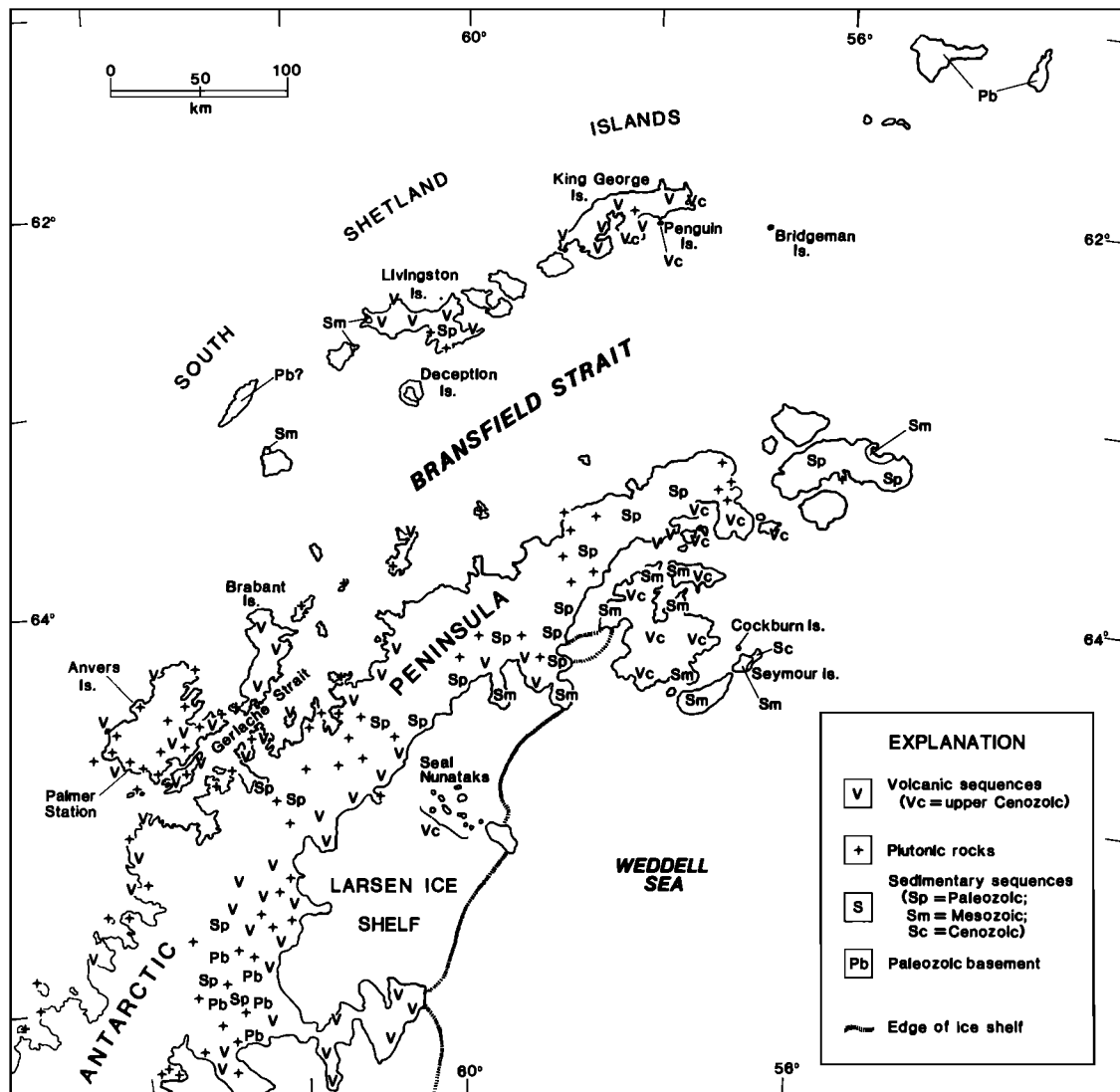


Fig. 2. Simplified geologic map of the northern Antarctic Peninsula [from Adie, 1969; *British Antarctic Survey*, 1979].

is related to widespread extensional tectonism in the region. Sedimentary rocks younger than upper Eocene are confined to glaciomarine beds on Cockburn Island [Zinsmeister and Webb, 1982], on Seymour Island [Zinsmeister and DeVries, 1983], and in the South Shetland Islands [Birkenmajer, 1982b; Smellie et al., 1984; Birkenmajer and Luczkowska, 1987]. Alkali basaltic rocks (6 m.y. and younger) are present in the James Ross Island area, and to the south at the Seal Nunataks [Rex, 1976], where fumarolic activity still is occurring [Gonzalez-Ferran, 1983]. In the South Shetlands, scattered outcrops of upper Tertiary (?) and Quaternary basaltic and andesitic plugs, dikes, and lava flows are present from eastern Livingston

Island to King George Island [Birkenmajer, 1980d; Smellie et al., 1984]. The active and recently active centers of volcanism on Deception, Penguin, and Bridgeman islands lie approximately along the boundary between the South Shetland Islands platform and the marginal basin that underlies the Bransfield Strait. Deception and Bridgeman islands are situated along the axial magnetic anomaly in the Bransfield Strait, and together with Penguin Island they likely chronicle early stages of opening of the strait, marking the change from subduction-related compressional tectonics to intraplate tensional tectonics [Weaver et al., 1979, 1982; Birkenmajer, 1982a; Smellie et al., 1984; Gonzalez-Ferran, 1987].

MINERALIZATION

The region of interest (Figures 1 and 2) lies within the Andean Metallogenic Province, as defined by Rowley *et al.* [1983]. Except for the well-documented mineralization of the Lassiter Coast [Rowley *et al.*, 1977], which occurs in Cretaceous plutonic rocks, the widespread traces of mineralization along the northwest margin of the Antarctic Peninsula are associated mainly with Tertiary rocks. Wright and Williams [1974], Erickson [1976], and Rowley and Pride [1982] have pointed out that the Antarctic Peninsula and the southern Andes are not as mineral-rich as are the Andes north of the Chile Rise. Comparisons between the mineralized Andes and the northern Antarctic Peninsula are difficult. Different segments of ocean crust were subducted in the two regions, and not enough is known of the rates and angles of subduction with respect to mineralization, nor of the composition of the ocean crust that was being subducted, or the characteristics of the rocks that were penetrated by mineralizing intrusions. In general, however, the ages and characteristics of intrusions in the Antarctic Peninsula are similar to intrusions that carry porphyry and related base and precious metal mineralization in the Andean cordillera of South America, and the tectonic style of the northern Antarctic Peninsula appears to be similar to that part of Chile in which the porphyry and related deposits are found. Deformation in both regions was characterized by block faulting and gentle warping of the rocks, and by the absence of penetrative structures [Dalziel, 1981].

Efforts in the present study were directed to the location of hydrothermal alteration and mineralization associated with high-level calc-alkaline plutonic systems. Large-tonnage ("porphyry"-type) deposits of copper, molybdenum, and tin in the highly mineralized part of the Andes are associated with calc-alkaline intrusions, and these systems also spawned vein deposits of lead, zinc, gold, and silver. Where intrusions of this type penetrate reactive host rocks, they also may produce replacement deposits that contain tungsten and tin, plus copper, molybdenum, lead, zinc, gold, and silver. In addition, near-surface, low-temperature deposits of gold, silver, and mercury may form from circulating hydrothermal fluids of largely meteoric origin that are driven by heat given off during cooling of the igneous systems. Thus the present investigation has relied heavily on the presumed association between "Andean-type" intrusive activity and most types of potentially significant mineralization.

Alteration and mineralization in porphyry-metal systems typically are centered on composite epizonal stocks in which at least one of the igneous phases is porphyritic. The intrusive complex often is part of a volcanic superstructure, and intrusive breccias (breccia pipes) may form in systems with high fluid pressures. The alteration mineralogy will vary according to the

compositions of the intruded and intruding rocks but, in general, ranges from inner potassium silicate (K-feldspar, biotite), to sericite and clay minerals, to peripheral chlorite and epidote plus carbonate. Secondary quartz is a common component of the alteration, and in extreme cases it may "flood" the system, obliterating most other mineral phases. Copper and molybdenum sulfides dominate the inner mineralization, which grades outward through zones dominated by lead and zinc sulfides, and finally to the precious metals gold and silver. Pyrite is ubiquitous to the mineralization, and there may be considerable overlap of the mineral zones and "telescoping" of the mineralization if the fluids are channeled along major fractures.

FIELD AND LABORATORY STUDIES

Three areas in the northern Antarctic Peninsula were chosen for study, based upon published information and discussions with scientists who had visited the region. The localities are (1) King George and Livingston islands in the South Shetland Islands, (2) the Gerlache Strait, between Anvers Island and the mainland coast, and (3) the vicinity of Palmer Station, southern Anvers Island (Figures 1 and 2). The region is largely covered by snow and ice; so access was limited largely to rock outcrops along coastlines and on promontories and small peninsulas. The field portion of the research was conducted during the austral summers 1980 and 1981. Access to the field areas was by zodiac from R/V *Hero* and on foot from tent camps. Work in the vicinity of Palmer Station was done on foot from the station. Field investigations included geologic mapping where possible, plus collection of samples for petrographic studies and chemical analyses. About 450 sample stations were established. Hand specimens and composite rock chip samples consisting of 10 to 20 small chips were collected to provide representative samples of altered and mineralized rocks. Whenever possible, sampling was of vein material because veins represent sites of focused hydrothermal flow. All indications of pervasive alteration and mineralization also were carefully sampled, and unmineralized material was collected to establish the background for the altered and mineralized samples.

Chemical analyses and petrographic studies that included thin sections, polished surfaces, and fluid inclusion analyses were conducted at the Ohio State University. A total of 317 composite rock samples were analyzed by atomic absorption spectrophotometry and colorimetry for copper, lead, zinc, gold, silver, molybdenum, and tungsten (Tables 1-7). Gold analyses for samples collected during the 1981 field season were done by atomic absorption at Skyline Labs, Inc., Denver, Colorado.

TABLE 1. Trace Element Data From Rock Chip Samples, King George Island

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
<i>Keller Peninsula</i>								
Andesite	1	42		58				
	2	116	38	80				
	5	117		72				
	6	109	2	56				
	7	125		83				
	9	260		83				
	12	15		86				
	13	125		84		1		
	14	67		104				
	15	90	13	101				
	16	70		102				
	17	51		40				
	19	137	21	93				
	20	100	29	112				
	21	64	36	90				
	22	54	20	80				
	23	73	2	66			2	
	24	84	3	60				
	25	74		63				
	26	53		47				
	29	11						
	33	195	13	149			2	
	35	114	28	83			1	
	38	113		90				
	40	171	36	141				
	44	46	25	77				
	45	122		142				
	46	70	16	104				
	60	84	18	89				
	62	81	57	100				
	63	46		66				
Tuff	11	66		59		2		
	18	50		42				
	27	133		2		5		
	28	61		13		2		
	30	42		2				
	31	94		60		2		
	32	175		126		1		
	34	14				3		
	48							
	49	6		11				
	50	34						
	58							
	59							
Agglomerate	36	117	21	87		2		
	37	93		57		2		
	39	60	28	62				
	41	102		116				
	42	2		117				
	43	16	25	77				
Diorite (Andean Intrusive Suite)	52	12	10	6				
	55	144	31	82				
	56	155	27	80				
	57	146	27	77				
Dike	67	90	28	122				
	68	49	25	91				
	69	58	18	97				
Tectonic breccia	3	306		57			4	
	4	102	54	52		3		
	64			21				
Intrusive contact breccia	65	69		81				
	51	14						
	53	13						

TABLE 1. (continued)

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
Quartz vein	66	51	18	93				
	47	187		49				
	54	7		8				
	61	78	9	27				
<i>Barton Peninsula</i>								
Andesite	78	219	43	64	D			
	81	342	39	119		2	2	
	83	173	177	135				
	85	162	27	112	D	2		
	88	6	2	79				
	114	120	25	75				
	115	164	25	79				
	116	115	2	67				
	117	54	2	63				
	123	147		84				
	124	37	2	84				
	125	289	2	90				
	126	175	12	78				
	127	854	14	57	D			
	128	35	13	114				
	131	87	15	97				
	134	85	2	71				
	135	83	2	65				
	136	103	2	107				
	137	137	2	105				
	138	148	2	62				
	139	153	2	58				
	141	157	2	85				
	142	4						1
	143	80	23	80				1
	144	93	22	63				
	145	107	2	67				
	158	180	2	50				
Agglomerate	118	100	2	73				
	129	87	15	97				
	130	64	2	94				
	132	256	24	58				
	133	149		100				
Hornfels	108			64				
	111	141	14	26				3
	112	176	14	73				2
	113	243	23	57	D			3
Granodiorite-quartz diorite (Andean intrusive suite)	71	75	10	80				
	72	87	33	82				
	73	55	27	65				
	75	79	46	58				2
	76	233	41	87				
	77	40	51	88				3
	79	121	31	70				3
	94	103	2	65				
	101	50	2	42				
	102	114	3	81				
	104	75		65				
	106	49		73				2
	107	68	2	60				2
	109	70	16	130				
	110	94	14	112				
	150	95	2	70				1
	154	103	2	65				
	155	19	13	57				
	157	124	2	74				
Diorite (Andean intrusive suite)	80	2,192	27	156				5
	90	198	2	43	D	2		5
	92	110	2	57				

TABLE 1. (continued)

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
	93	78	2	37	D	1		
	95	202	22	99	D			
	97	151	33	116				
	99	113	2	124		3		
	100	43	14	40				
	146	249	16	153	D			
	147	511	13	164		6		
	148	506	21	300		12		
	149	115	14	92				
	152	94	2	31		1		
	159	174	14	50				
	160	101	24	52				
	161	135	59	92				
	162	41	2	61				
	163	147	21	102				
	164	20	2	62				
Dike (aplite)	74	123	41	70			2	
	82	382	17	42				
Tectonic breccia	86	145	35	156	D		4	
	120	68		33				
Intrusive contact breccia	98	116	14	106				
	102	111		94				
Xenoliths (in Andean intrusive)	151	502	2	93				
	153	6,247	2	56			1	
Quartz vein	90	198	2	43	D	2	5	
	103	11	3				3	
	140	11	2				2	
Altered rocks (andesite, along fault)	84	54	69	45	D	2	3	
	87	194		109				
	89	141	24	114	D	4	13	
Soil 92	110	2	57					
	121	70	27			2		
	156	227	45	136		2		

Abbreviations: ppm, parts per million; ppb, parts per billion; D, detected but not in measurable quantities.

King George Island, South Shetland Islands

Quartz-pyrite vein and replacement bodies have been reported from several localities on King George Island (Figure 3a). *Ferguson* [1921] mapped a large quartz-pyrite replacement deposit in volcanic rocks west of North Foreland in the northeastern part of the island, and he described two large quartz-pyrite replacement deposits on Keller Peninsula in Admiralty Bay; *Ferguson* [1921] and *Tyrell* [1921] described quartz veins, pyrite, and hydrothermally altered rocks from the western end of the island; *Barton* [1965] reexamined the two quartz-pyrite replacement bodies on Keller Peninsula, and he mapped pyritized andesites cut by large quartz-pyrite replacement bodies near Noel Hill on Barton Peninsula and at Potter Cove on the southeastern side of Barton Peninsula; *Barton* also mapped altered "upper Jurassic" and Tertiary volcanic rocks containing disseminated pyrite, calcite, and quartz on Fildes Peninsula; *Grikurov and Polyakov* [1971a, b] described silic-

ified and pyritized rocks near Bellingshausen Station, also on Fildes Peninsula; and *Birkenmajer* [1980d] mapped the geology of Admiralty Bay and briefly discussed the quartz-pyrite mineralization on Keller Peninsula. According to *Ferguson* [1921], one of the quartz-pyrite replacement bodies on Keller Peninsula is more than 2 km long and as much as 155 m wide.

C. A. Cox and R. R. Conelea [Cox, 1981] mapped the geology of Keller and Barton peninsulas (Figures 3b and 3c) and collected 156 samples for petrographic study and chemical analysis (Table 1). The mapping was based in part on the work of *Birkenmajer* [1980a, b, c, d]. *Littlefair* [1978] studied the mineralized rocks on King George Island and concluded that the quartz-pyrite rocks were affected by low-temperature "hot springs"-type alteration that may represent the surface expression of porphyry-type mineralization at depth on the island, a conclusion reached also by *Hawkes* [1982]. According to Cox [1981], the alteration and mineraliza-

TABLE 2. Trace Element Data From Rock Chip Samples, Livingston Island

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
<i>Hurd Peninsula, South of Johnsons Dock</i>								
Andesite	108		30	84	2	2		
contact zone (108)	109		8	114	2	2		
Andesite	110	66	34	126	4	2		
Andesite	116	14	46	118	3	2		
Metagreywacke	107	48	100	300	4	2		
Metagreywacke	113		134	264	4	1		
Metagreywacke	114		46	116	4	1		
Metagreywacke	206	332	1,352	493	20	3		
Quartz vein	101	714	614	1,387	33	3		
Quartz vein	102	1,190	3,647	1,392	80	4		
wallrock (102)	103	122	150	1,561	5	2		
Quartz vein	104	2,298	7,074	1,800	35	8		
wallrock (104)	105	40	596	256	5	4		
Quartz vein	106	130	7,617	154	11	2		
Quartz vein	111	350	398	5,346	10			
Quartz vein, vein breccia	117	1,768	1,428	3,564	8	4		
Quartz and calcite vein	112		64	78	5	6		
<i>Hurd Peninsula, Vicinity of Johnsons Dock</i>								
Tonalite (?)	006	50	150	120				
Tonalite	016	99		77				
Andesite	201	28	43	137	2	2		
Basic intrusion	008	80	2	83				
fine-grain mafic rock	012	55	13	240				
Sandstone	003	75	23	185				
Sandstone	014			677				
Argillite	204	38	44	116	4	1		
Argillite and calcite veinlets	205	26	98	136	6	2		
Quartz vein	001	2,900	1,940	1,030				
Quartz vein	002	6	180	73				
Quartz vein	005	500	1,200	160				
Quartz vein	009	2		50				
Quartz vein	015	4,300	440	5,400				
Quartz vein	017	2,400	210	140				
Quartz vein	120	6,371	15,114	13,174	19	4		
Quartz vein breccia	121	1,720	252	592	25	4		
wallrock (121)	122	326	48	312	18	3		
Quartz vein breccia	202	6,215	338	815	180	8		
Calcite vein breccia	011	37	60	56,000				
Calcite vein	013	2	70	56				
<i>Hurd Peninsula, North of Johnsons Dock</i>								
Tonalite (?)	132	42	64	140	3	2		
Andesite	304	84	32	456	4	4		
Argillite (?)	305	26	22	122	5	4		
Quartz vein	129	3,119	822	2,771	85	10		
wallrock (129)	130	3,073	7,039	340	570	6		
country rocks (129, 130)	131	64	44	303	5	2		
Calcite vein	132		86	104	4	10		
<i>Northeast False Bay</i>								
Quartz monzonite (min)	200	2,432	25	72	15		3	
Quartz monzonite (min)	203	2,663	8	79	15	3	D	D
Quartz monzonite (min)	303	9,704	8	64	50	4	420	11
Granodiorite and sulfide veins	102	1,083	20	52	30	4	3	

TABLE 2. (continued)

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
Granodiorite	104	118	6	40	4	3	D	
Monzonite (min)	304	9,504	8	56	10	3	D	17
Diorite	106	16	8	114	7	4		
Diorite	300	40	12	22	4	3		
Quartz vein	105	42	2	1	1		D	
K-feldspar vein	202	14	8	7	3	3		

Abbreviations: ppm, parts per million; ppb, parts per billion; D, detected but not in measurable quantities.

tion on both Keller and Barton peninsulas probably are not porphyry in character but developed during devolatilization of diorite and granodiorite-quartz diorite magmas as they crystallized. In a review of published data on King George Island, *Willan* [1987] concluded that the mineralization could have been volcanogenic or high-level epithermal in origin, related to gabbroic or granodioritic intrusions.

Alteration and mineralization on both Keller and Barton peninsulas likely were related genetically to formation of the igneous rocks (Figures 3b and 3c). Copper (Table 1) is the only element that is anomalous,

although traces of gold, silver, and molybdenum are present, silver to 12 ppm. The small number of quartz veins that were sampled contain very little metal. The diorite on Keller Peninsula averages 114 ppm copper (4 samples); and granodiorite-quartz diorite and diorite on Barton Peninsula average 87 ppm and 166 ppm copper, respectively, for 19 and 18 samples (Table 1). Sample 80 (diorite) was excluded from the calculation for Barton Peninsula, as it was collected from near a fault (Figure 3c), and very likely was mineralized following crystallization. Andesites on Keller Peninsula average 93 ppm copper (31 samples), and on Barton Peninsula, they average 150 ppm copper (28 samples).

King George Island is more than 90% covered with ice [*Birkenmajer*, 1980d], which makes conclusions concerning the presence of significant mineralization on the island difficult. To illustrate, two small pebbles of argillized, sericitized, and pyritized tuff were found during examination of samples from piston core PC-85-49, taken in Admiralty Bay (Figure 3a). The samples apparently did not come from exposures in the immediate vicinity, but they are similar to material from porphyry copper and molybdenum deposits and from mineralized veins. Copper contents in the pebbles are not high (24 and 91 ppm), but molybdenum is anomalous in the pebble with the highest copper (21 ppm), and the other pebble contains 217 ppb (0.217 ppm) gold.

TABLE 3. Average Metal Concentrations in Veins, Hurd Peninsula, Livingston Island

	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm
<i>South of Johnsons Dock (7)*</i>					
Mean	921	2,977	1,960	26	3.9
Range	0-2,298	64-7,617	78-5,346	5-80	0-8
<i>Vicinity of Johnsons Dock (12)*</i>					
Mean	2,199	2,450	6,696	60†	4.8†
Range	2-6,371	0-15,114	50-56,000	14-180	3-8

*Number of samples analyzed.

†Only four samples analyzed for gold and silver.

Abbreviations: ppm, parts per million; ppb, parts per billion.

TABLE 4. Average Metal Concentrations in Mineralized Intrusive Rocks and Veins, Northeast False Bay, Livingston Island

	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
<i>Mineralized Intrusions (5)*</i>							
Mean	5077	14	65	24	2.8	85	5.6
Range	1,083-9,704	8-25	52-79	10-50	0-4	D-420	0-17
<i>Veins (2)*</i>							
Mean	28	5	4	2	1.5		
Range	14-42	2-8	1-7	1-3	0-3		

*Number of samples analyzed.

Abbreviations: ppm, parts per million; ppb, parts per billion.

TABLE 5. Trace Element Data From Rock Chip Samples, Gerlache Strait

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
<i>Eckener Point</i>								
Argillite	EP-101	28	40	128	2	3		
Argillite and epidote veins	EP-201	16	1,173	140	6	66		
Monzonite	EP-202	14	14	104	3	4		
Chert	EP-301	36	10	36	5	152	D	D
<i>North of Bahia Frei (Recess Cove)</i>								
Volcanic (?) mineralized	NBF-102	740	89,292	29,027	4	44		
Metasedimentary rocks	NBF-301	160	40	84	9	5		
<i>Island in Bahia Frei (Recess Cove)</i>								
Quartz monzonite	BFI-101		23	27	4	3		
Quartz monzonite	BFI-102		18	25	7	3		D
Quartz monzonite	BFI-103		11	26	25	5		
Mafic dike	BFI-104	28	36	140	4	5		D
<i>Marc Peninsula</i>								
Rhyolite (?)	M-106	8	16	85	17	3		D
Rhyolite	M-108	8	8	42	13	3		
Fine-grain granite	M-110		8	76	4	2		
Andesite	M-107	8	14	97	10	3		8
<i>Pelseneer Island</i>								
Silic. brecciated rhyolite	PI-101	70	14	18	180	3	D	
Silic. brecciated rhyolite	PI-102		14	34	3	3	D	
Silic. brecciated rhyolite	PI-103		14	62	D	3	D	
Silic. brecciated rhyolite	PI-104		8	34	D	1	D	
Silic. brecciated rhyolite	PI-105		20	28	6	6	D	
Silic. brecciated rhyolite	PI-106		4	42	3	160	D	
Silic., veined, brecciated rhyolite	PI-107	10	2	96	D	1	D	D
Argillite (?)	PI-109	21	25	72	D	8	D	D
<i>Thompson Peninsula (Anvers Island)</i>								
Diorite	TP-105	18	22	112	3	4		
Diorite	TP-107	54	12	98	4	4		D

Abbreviations: ppm, parts per million; ppb, parts per billion; D, detected but not in measurable quantities.

Livingston Island, South Shetland Islands

Caminos et al. [1973] mapped quartz and calcite veins containing chalcopyrite, covellite, galena, pyrite, and sphalerite, plus secondary copper carbonates and iron oxides on Hurd Peninsula, south of Johnsons Dock (Figures 3a and 3d). The mineralization is localized along faults in folded sedimentary rocks of the Miers Bluff Formation. In studying this occurrence, *del Valle et al.* [1974] also identified tetrahedrite, tennantite, chalcocite, bornite, linarite, antlerite, cerrusite, and

witherite. *Willan* [1987] examined the area and described veins and vein-breccias containing sphalerite, galena, chalcopyrite, and pyrite that can be traced along strike for as much as 3000 m.

Short (2–3 day) trips were made to the west side of Hurd Peninsula during 1980 and 1981 to examine the geology and to collect samples for laboratory study. Efforts were concentrated in the vicinity of Johnsons Dock (Figure 3d). In addition, one-half day was spent examining the small body of tonalite north of Johnsons

TABLE 6. Trace Element Data From Rock Chip Samples, Southern Anvers Island and Nearby Islands

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
<i>Gamage Point-Bonaparte Point</i>								
Tonalite	AH-013	350		46				
Tonalite	AH-015	270	140	39				
Tonalite	AH-020	511	12	43				
Tonalite	AH-117	166	22	106	5	34		
Tonalite	AH-131	82	24	52	5	2		
Tonalite	AH-141	16	14	28	2	230		
Tonalite	AH-143	20	17	54	2	4		
Tonalite	AH-145	26	12	62	2	3		
Tonalite	AH-202	168	18	82	5	4		4
Tonalite	AH-203	68	14	52	4	3	1	
Tonalite (min)	AH-012	800		71				
Tonalite (min)	AH-014	815	111	45				
Tonalite (min)	AH-016	7,000	50	130				
Tonalite (min)	AH-018	470	20	27				
Tonalite (min)	AH-021	800		55				
Tonalite (min)	AH-022	107	11	70				
Tonalite (min)	AH-109	156	14	104	3	119		4
Tonalite (min)	AH-400	166	22	82	3	14		
Trondhjemite	AH-137	36	32	24	2		1	
porphyry								
Pegmatite	AH-120	2,267	12	60	10		21	8
Pegmatite	AH-128	52	514	68	4	4	8	4
Quartz vein	AH-017	20,000	100	400				
Quartz vein	AH-019	560	550	900				
Vein	AH-113	7,824	14	154	745	103	280	4
Vein	AH-119	622	12	28	4		21	6
Vein	AH-124	42	7,096	256	3,100	4	2	39
Vein	AH-127	8,553	8	176	180	21	566	5
Vein	AH-132		6	2	2	4		4
wallrock (132)	AH-133	124	18	50	3	2	1	
Vein	AH-135	130	530	140	570	2	70	6
wallrock (135)	AH-136	1,288	407	782	45	2	21	4
Vein	AH-138	1,069	6	46	10	6	11	
Vein	AH-139	901	46	110	2	2	2	
Vein	AH-221	571	8	36	14	3		
Vein	AH-301	3,906	20	66	10	3	1	
<i>Norsel Point-Old Palmer</i>								
Trondhjemite	NP-008	15	290	44				
Trondhjemite	NP-009	7	27	60				
Trondhjemite	NP-007	14	80	150				
porphyry	NP-011	170	12	155				
Trondhjemite	NP-203		16	64	5	4		
porphyry								
Diorite	NP-201	10	18	136	3	4		4
Diorite	NP-301		12	32	4	4		
Diorite	NP-302	44	12	182	4	4		
Contact breccia (diorite)	NP-006	6	25	72				
Lamprophyre (?) dike	NP-010	54	10	115				
Vein	NP-204	216	8	44	30	4	1	4
Vein	NP-304	29	18	54	9	5	1	4
Vein	NP-305	797	10	39	30	2		6
<i>Torgersen Island</i>								
Diorite	TI-103		28	24	1	5		
Diorite	TI-105		10	70	9	3		
Volcanic	TI-002	6	182	73				
Volcanic	TI-201	370	14	134	5	4		
Volcanic breccia	TI-004	15	46	102				

TABLE 6. (continued)

Rock and Mineral Association	Sample Number	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
Volcanic breccia	TI-302	18	14	142	6	2		
Silicified skarn	TI-005	7	43	50				
<i>Litchfield Island</i>								
Diorite	LI-101		22	42	2	3		
Diorite	LI-201		30	52	3	3		
Diorite	LI-202		14	60		67		
Diorite	LI-204	255	12	86	40	3		
Diorite	LI-301		16	118	2	3		
Diorite	LI-302		3,154	48		14		
Diorite	LI-303	10	6	32	11	2	1	
<i>Shortcut Island</i>								
Tonalite	SC-101	52	12	12	46	75		1
Tonalite	SC-201	18	12	46	1	1	4	
<i>Christine Island</i>								
Tonalite	CI-104	66	12	47	2	2		
Tonalite with veinlets	CI-103	3,139	20	57	70	3	2	
Feldspar vein	CI-202		8	8	2	2		4
<i>Humble Island</i>								
Trondhjemite porphyry	HI-201		10	72		2		4
Diorite	HI-101	10	16	98	3	10		
<i>Breaker Island</i>								
Trondhjemite porphyry	BR-549	32	14	54	6	4		
Diorite	BR-101	18	12	74	3	4		
<i>Cape Monaco</i>								
Granite	CM-101	14	10	51	3	3		
Granite	CM-106		22	57	3	3		
Granite	CM-201		14	37	4	2		
Granite	CM-203		14	48	2	2		
<i>Joubin Islands</i>								
Volcanic	JI-101		8	38	4	8		
Volcanic (min)	JI-103		19,360	42	4	135	3	4
<i>Gossler Islands</i>								
Granite	GI-105	10	20	42	2	48		

Abbreviations: ppm, parts per million; ppb, parts per billion.

Dock. Where examined, hydrothermal alteration and mineralization occur in veins and vein-breccias; mineralized structures contain visible galena, pyrite, chalcopyrite, and sphalerite, and samples of vein material and wallrock are highly anomalous in copper, lead, zinc, gold, and silver (Tables 2 and 3). Several of the samples contain more than 1% combined copper, lead, and zinc, and the wallrock to sample 129 (Figure 3d) contains 570 ppb gold.

Camino et al. [1973] and *del Valle et al.* [1974] concluded that the alteration and mineralization on Hurd Peninsula were generated by the tonalite pluton

that forms Barnard Point east of False Bay. In the opinion of the writers, however, the mineralization more likely is related to the small tonalite intrusion noted by *Hobbs* [1968] north of Johnsons Dock. Where it was examined, the tonalite is quite fresh, but the intensity of the mineralization on Hurd Peninsula increases from south to north, and this coupled with the presence of sulfide veining in the vicinity of the tonalite suggests that another (mineralized) igneous phase may be present in the area.

One day was spent in 1981 examining the area north-

TABLE 7. Average Metal Concentrations in Veins, Arthur Harbor Area, South Anvers Island

	Cu, ppm	Pb, ppm	Zn, ppm	Au, ppb	Ag, ppm	Mo, ppm	W, ppm
<i>Gamage Point (12)*</i>							
Mean	3,682	700	193	386	12.3	73	5.3
Range	0-20,000	6-7,096	2-900	0-3,100	0-103	0-566	0-39
<i>Norsel Point-Old Palmer Station (3)*</i>							
Mean	347	12	46	23	3.7	0.7	4.6
Range	29-797	8-18	39-54	9-30	2-5	0-1	4-6

*Number of samples analyzed.

Abbreviations: ppm, parts per million; ppb, parts per billion.

east of False Bay (Figure 3e). Investigations there were based on reports that glacially derived boulders of granodiorite along the shoreline are cut by veinlets of molybdenite and that malachite also stains the boulders (J. E. Curl, personal communication, 1975). The boulders probably originated in the area to the northeast of Charity Glacier (Figure 3e). Rocks ranging in composition from granodiorite to quartz monzonite, plus aplite and pegmatite were found along the shore, and it is believed that they are members of an intrusive complex that herein is named the North False Bay igneous complex. Veinlets carrying quartz, pyrite, chalcocopyrite, molybdenite, and sphalerite were found in several of the boulders. Trace metal contents of samples from the area are presented in Table 2, and Table 4 summarizes the

data for "mineralized" intrusive rocks and for veins in the northeast False Bay area. The mineralized rocks are not pervasively mineralized, nor do they exhibit significant alteration, but the veinlets are so small that they could not be individually sampled. Copper clearly is the most anomalous trace metal in the rocks, and the presence of molybdenum while "spotty" in occurrence is potentially significant. The mineralization could have been generated in a porphyry-type copper-molybdenum system, but it apparently was precipitated at some distance from the center of igneous-hydrothermal activity. Liquid plus vapor fluid inclusions in quartz from sample FB-102 yield homogenization temperatures between 265° and 270°C, which means that the fluids were quite "cool" at the time of mineralization. Quartz and

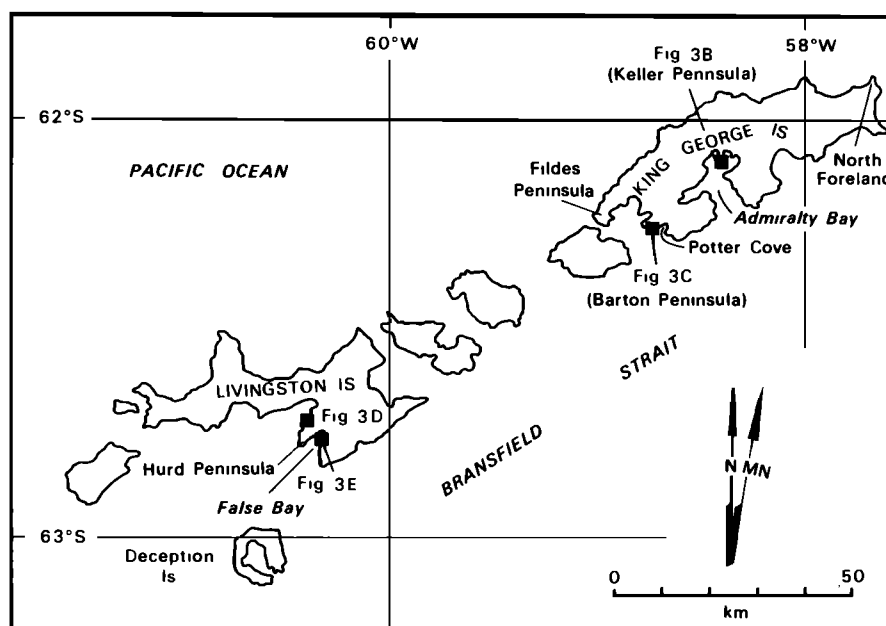


Fig. 3a. South Shetland Islands. Locations of Figures 3b-3e shown.

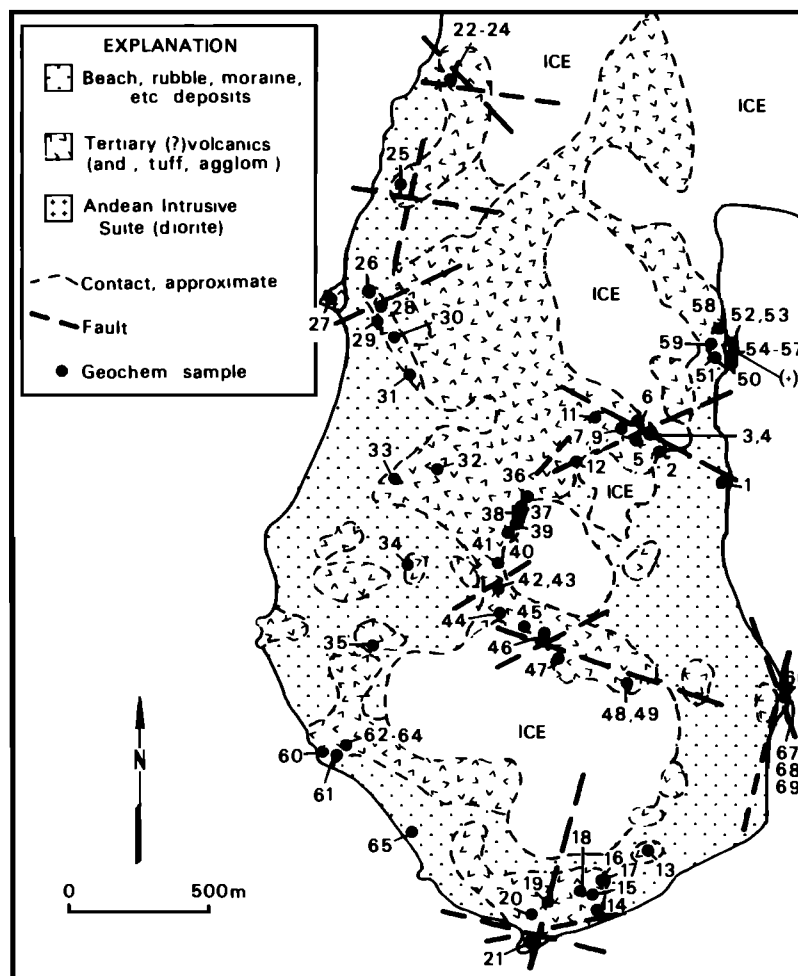


Fig. 3b. Keller Peninsula, King George Island. Geology modified from Cox [1981].

K-feldspar veins that were found in the plutonic rock suite could have been generated within the same igneous-hydrothermal system that spawned the veinlets in the mineralized rocks, but the trace metal contents are very low in the samples that were collected for study (Table 2 and 4).

Gerlache Strait

The geology of the Gerlache Strait is poorly exposed but consists generally of metamorphosed clastic sedimentary rocks that have been intruded by phases of the Andean Intrusive Suite. Alarcón *et al.* [1976] described the geology and mineralization of the region, including the areas of interest in the present study (Figures 4a–4f). The metasedimentary rocks shown in Figures 4b through 4e are metagraywackes and quartzites of the

Wilhelmina Bay Facies, and metamorphose pelitic rocks (slates, phyllites) of the Gandara Island Facies, both of the Charlotte Bay Formation [Alarcón *et al.*, 1976]. These rocks correspond to the Trinity Peninsula Formation of Adie [1969] and *British Antarctic Survey* [1979]. The sedimentary rocks range in age from Carboniferous (?) to Triassic, and they were intruded in the region of interest by granites, quartz monzonites, and diorites of the Andean Intrusive Suite.

According to Alarcón *et al.* [1976], mineralization in the Gerlache Strait region can be divided into several metallogenic provinces, namely, porphyry copper, copper vein (Cu sulfides), polymetallic veins (Cu-Pb-Zn-Ag sulfides), and magmatic iron. Except for the magmatic iron on Brabant Island (Figure 4a), the mineralization in the metallogenic provinces could have been produced in

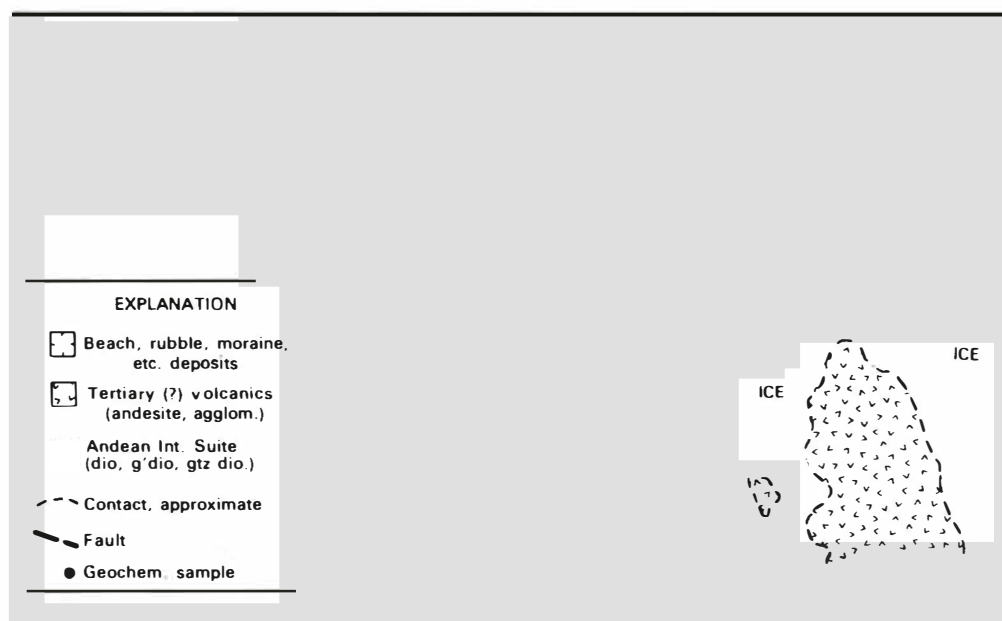


Fig. 3c. Barton Peninsula, King George Island. Geology modified from Cox [1981].

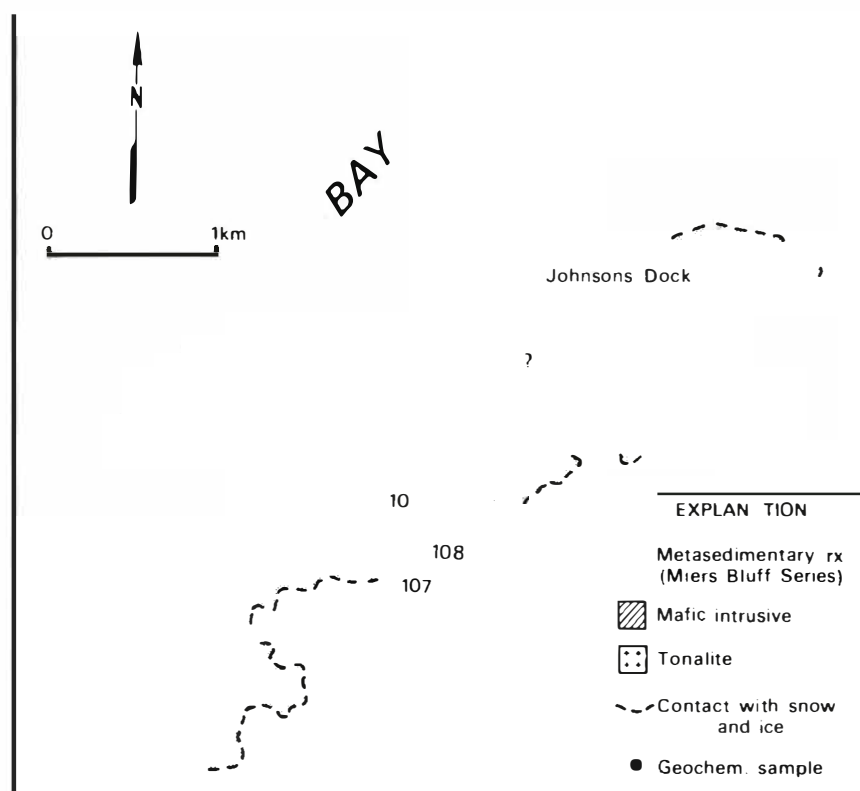


Fig. 3d. Vicinity of Johnsons Dock, northwest Hurd Peninsula, Livingston Island. Coastline and ice margin from aerial photographs. Geology from Hobbs [1968] and Smellie *et al.* [1984].

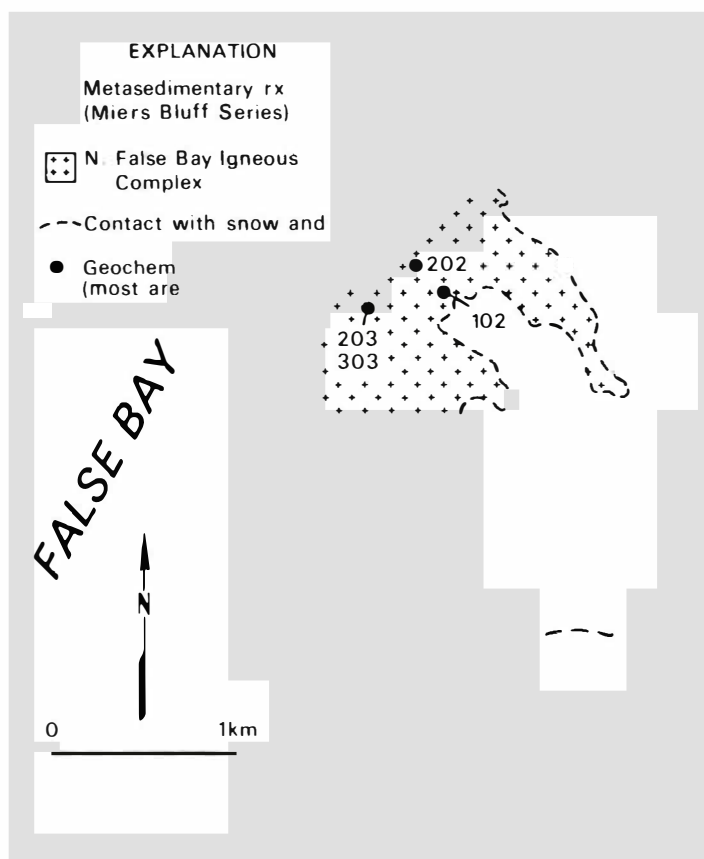


Fig. 3e. Northeast False Bay, Livingston Island. Coastline and ice margin from aerial photographs. Geology modified from *Smellie et al.* [1984].

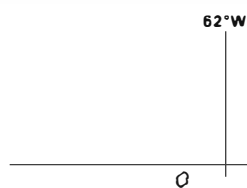


Fig
4C

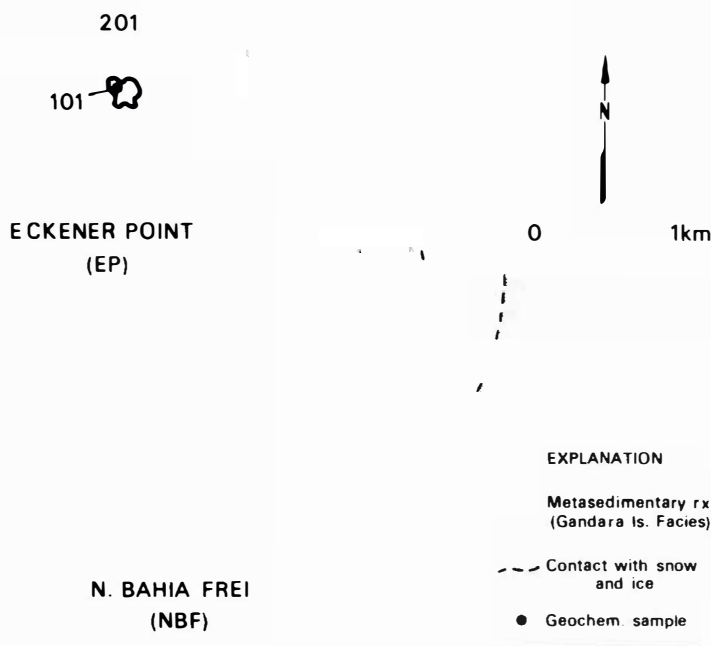


Fig. 4b. Eckener Point and region north of Bahia Frei (Recess Cove). Geology from *Alarcón et al.* [1976].

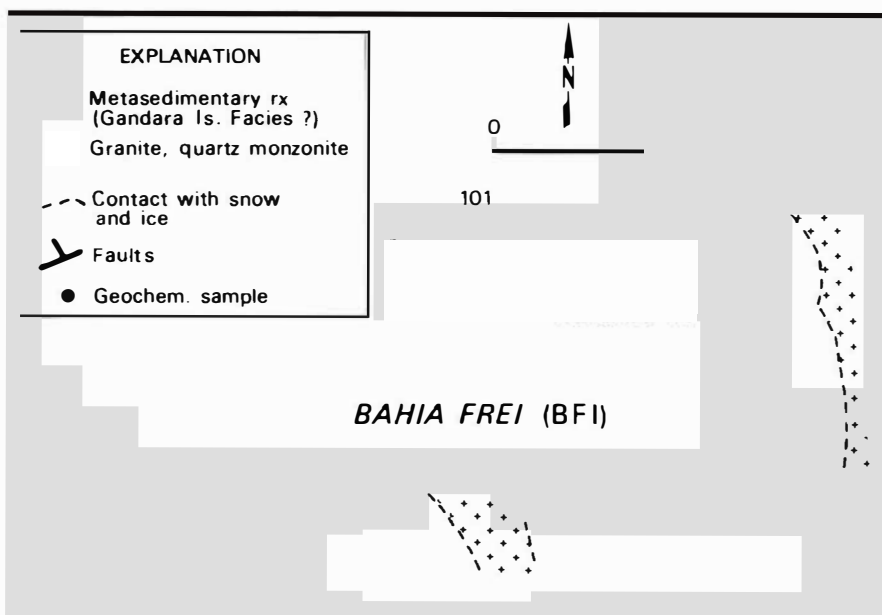


Fig. 4c. André Island in Bahia Frei (Recess Cove). Shorelines from aerial photographs. Geology modified from *Alarcón et al.* [1976].

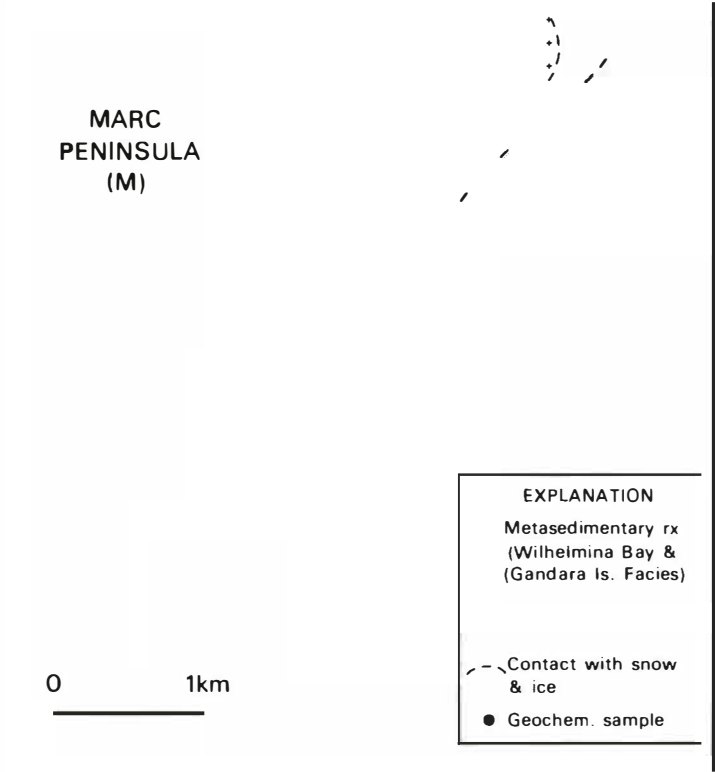


Fig. 4d. Marc Peninsula. Shoreline from aerial photographs. Geology from Alarcón *et al.* [1976].

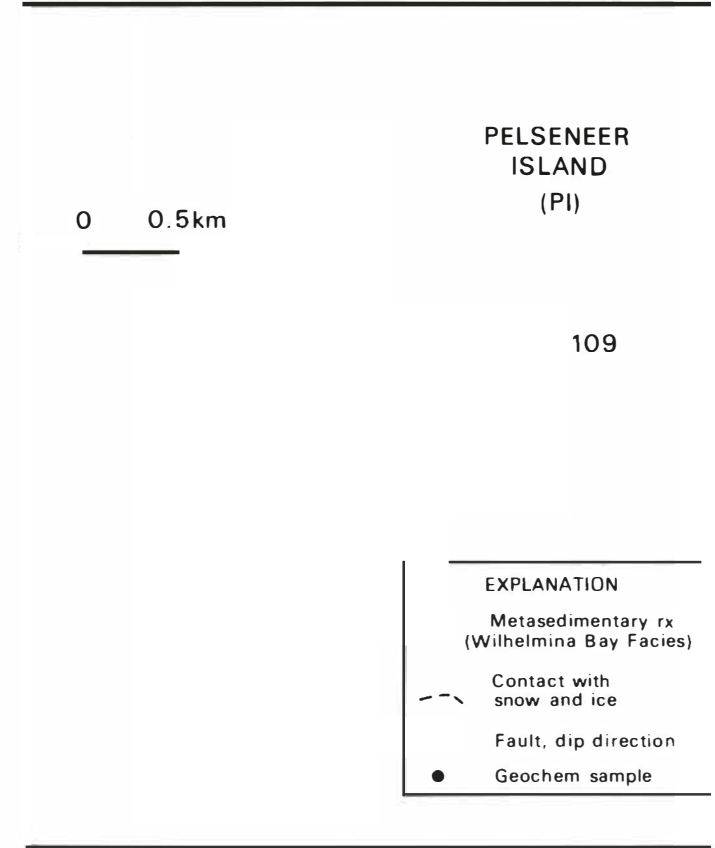


Fig. 4e. Pelseeneer Island. Shoreline from aerial photographs. Geology from Alarcón *et al.* [1976].

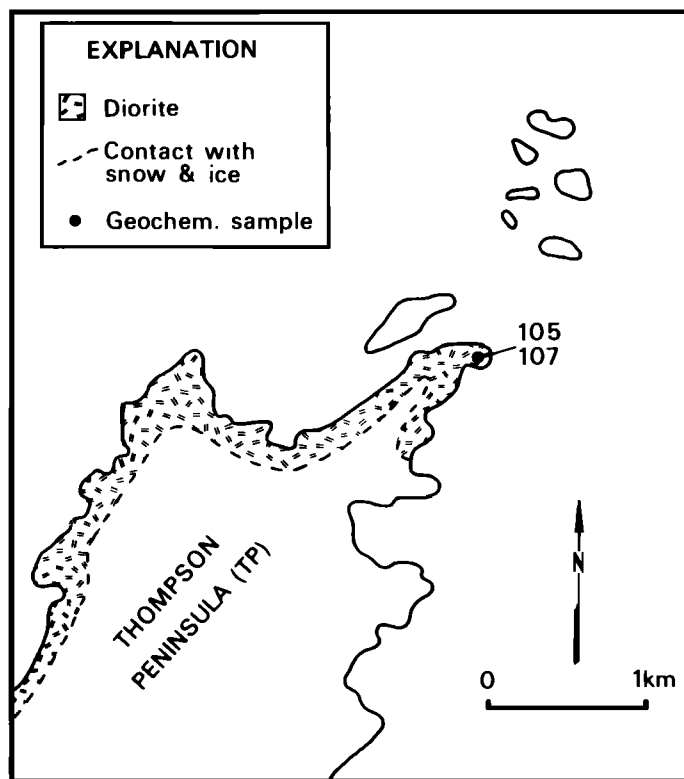


Fig. 4f. Thompson Peninsula, eastern Anvers Island. Geology from Alarcón *et al.* [1976].

porphyry-type systems, with current exposures reflecting different erosional levels and varying distances from centers of igneous-hydrothermal activity.

Field studies during 1981 in the Gerlache Strait generally revealed minor, fracture-controlled alteration and mineralization. Two localities are of interest: (1) a small area along the coast north of Bahia Frei (Recess Cove) and (2) Pelseneer Island in Wilhelmina Bay (Figures 4b and 4e). Individual samples from other localities are of some interest. For example, sample EP-201 from Eckener Point (Figure 4b) is anomalous in lead (Table 5), and it and EP-301 both carry considerable silver (66 and 152 ppm, which is equivalent to 1.9 and 4.5 ounces of silver per ton of rock).

Samples collected on Andrée Island in Bahia Frei (Figure 4c) are of little interest with respect to metallization, although they contain minor gold (Table 5). The trace metal contents of samples collected on Marc Peninsula (Figure 4d) are similar to those from Bahia Frei in that lead, zinc, and silver are quite low, but gold is present in slightly elevated concentrations (mean of 11 ppb for the four samples analyzed). The two samples that were collected on Thompson Peninsula (Figure 4f) are not anomalous in any of the trace metals studied.

Significant sulfide veining was noted in iron-stained

boulders along a spit north of Bahia Frei ("N. Bahia Frei" in Figure 4b). Veins ranging to 10 cm in thickness (generally less than 1 cm) contain pyrite, sphalerite, and galena, plus chalcocopyrite. One sample in particular (BF-102) contains more than 10% combined copper, lead, and zinc, plus 1.3 ounces per ton silver. Iron staining was noted in cliffs above the area where the samples were collected, but the exposures were not accessible. This small area contains some of the most interesting mineralization noted during the 1980 and 1981 field seasons, and it could be peripheral to a porphyry metal system located a short distance to the east or northeast.

The southern shore of Pelseneer Island (Figure 4e) is one of the two most pervasively altered localities visited in the Gerlache Strait-Anvers Island region. At one locality on the island, vertical exposures of silicified and pyritized rock were sampled from the bow of a zodiac (PI 101-107). Concentrations of copper, lead, and zinc are uniformly low in all of the samples that were analyzed (Table 5). Interestingly, however, sample PI-101 contains 180 ppb gold, and sample PI-106 contains 160 ppm silver. During the field visit, it was felt that the alteration and mineralization may have formed within a porphyry-type system. In retrospect, however, we feel

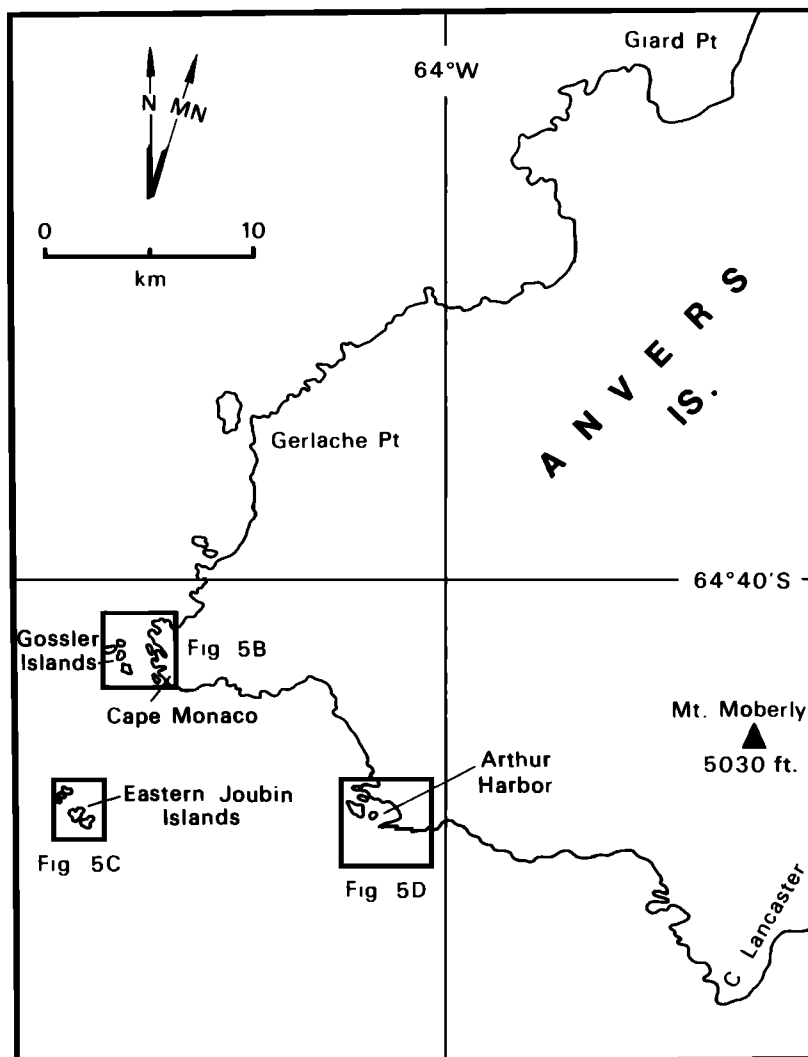


Fig. 5a. Southwest Anvers Island. From Defense Mapping Agency Hydrographic Center Map 29122, "Argentine Islands to Dallman Coast." Locations of Figures 5b–5d shown.

that the alteration and mineralization probably were produced by fluids moving along the major fault that crosses the island from south to north [Alarcón *et al.*, 1976]. The area from which samples PI 101–107 were collected is 150 to 250 m from that fault.

Anvers Island

Portions of the 1980 and 1981 field seasons were spent in the Arthur Harbor area, southwestern Anvers Island, and the 1981 season also included short visits to Cape Monaco and to the Gossler and Joubin islands (Figures 5a–5d). Samples were collected for petrography and for

chemical analysis (Table 6), and the geology was mapped whenever possible [Moody, 1982]. Interest in this part of Anvers Island was generated by descriptions of widespread metasomatism of rocks [Hooper, 1962] and of the presence there of polymetallic sulfide mineralization (Hooper [1962]; C. C. Plummer cited by Potter [1969]; Cox *et al.* [1980]; C. C. Plummer (written communication, 1977); W. J. Zinsmeister (personal communication, 1978)).

According to Hooper [1962], the oldest rocks on Anvers Island are upper Jurassic andesitic volcanics, which at one time probably covered much of the area. In the absence of radiometric and fossil dating, however, all that can be said is that the rocks formed some time

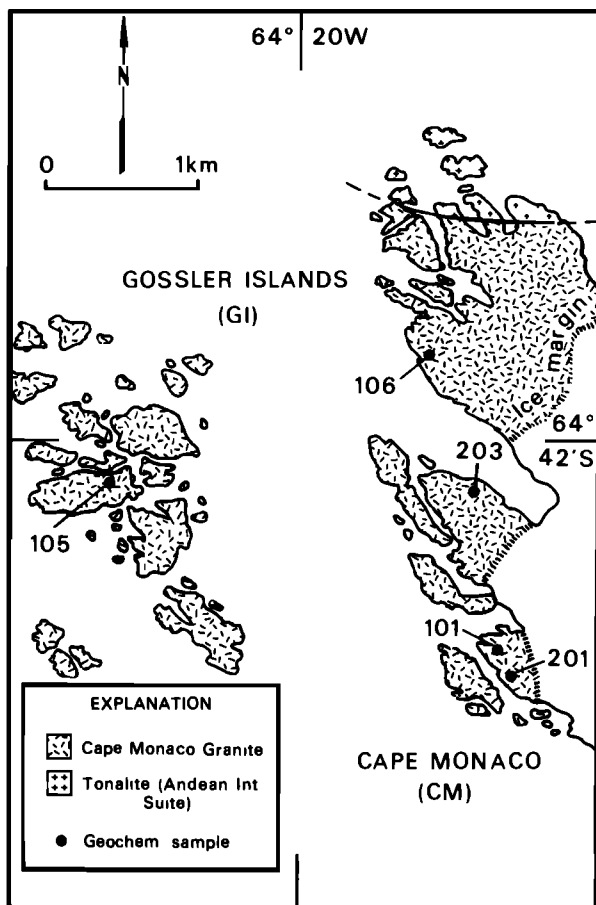


Fig. 5b. Cape Monaco and Gossler Islands. Geology from Hooper [1962].

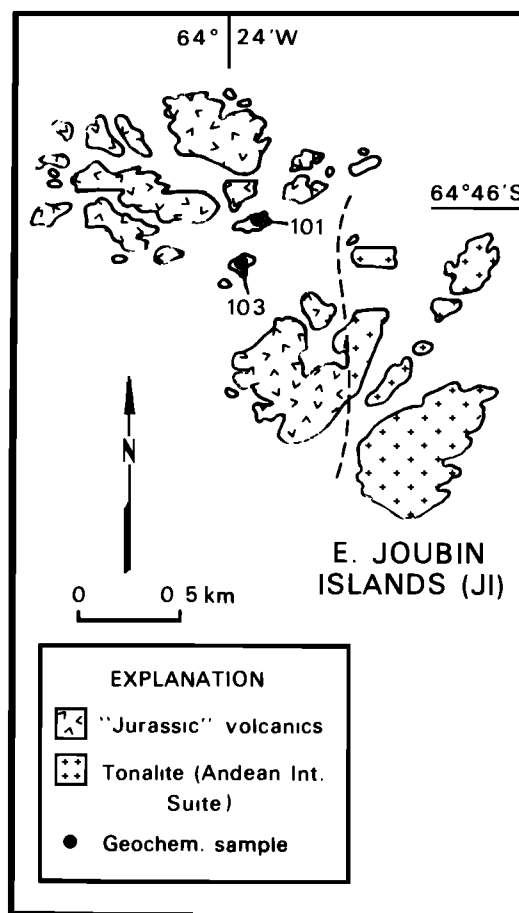


Fig. 5c. Eastern Joubin Islands. Geology from Hooper [1962].

between the early Jurassic and the early Tertiary [Thomson and Pankhurst, 1983]. The Andean Intrusive Suite in the Anvers Island region consists of gabbros, granodiorites, and "hybrid" rocks [Hooper, 1962], all of which probably are Tertiary in age [Gledhill *et al.*, 1982; Saunders *et al.*, 1982]. The hybrid rocks include tonalite, diorite, quartz diorite porphyry, trondhjemite, and trondhjemite porphyry. According to Hooper, the trondhjemite and trondhjemite porphyry and the Cape Monaco Granite of southwestern Anvers Island were formed by metasomatic alteration of a primary tonalite, and the diorite and quartz diorite porphyry were formed by metasomatic alteration of a rock equivalent to the "upper Jurassic" volcanics. Moody [1982] concluded that the plutonic rocks in the Arthur Harbor and Cape Monaco areas acquired their present characteristics through assimilation during emplacement and not by metasomatism as proposed by Hooper. In addition, Moody [1982] concluded that the andesitic volcanics exposed in the Arthur Harbor area [Hooper, 1962] may

have been extruded from a volcanic vent on Torgersen Island. The rocks of southern Anvers Island are cut by regional northeast-southwest and northwest-southeast structures, which provided pathways for magmatism, as well as for metasomatizing and mineralizing fluids [Hooper, 1962; Hawkes, 1982; Moody, 1982]. Moody also noted that the shapes of the offshore islands and the coast of the main island in the Arthur Harbor area are controlled by the northeast-southwest and northwest-southeast structures.

A small number of samples were collected for trace element analysis from Cape Monaco and from the nearby Gossler and Joubin islands (Figures 5b and 5c). The rocks in general are unaltered and unmineralized. One sample from a small vein in the Joubin Islands (JI-103, Table 6) contained almost 2% zinc and about 4 ounces per ton silver, but otherwise the rocks are fresh. Significant K-metasomatism of the Cape Monaco Granite was noted on the Gossler Islands, but it probably is

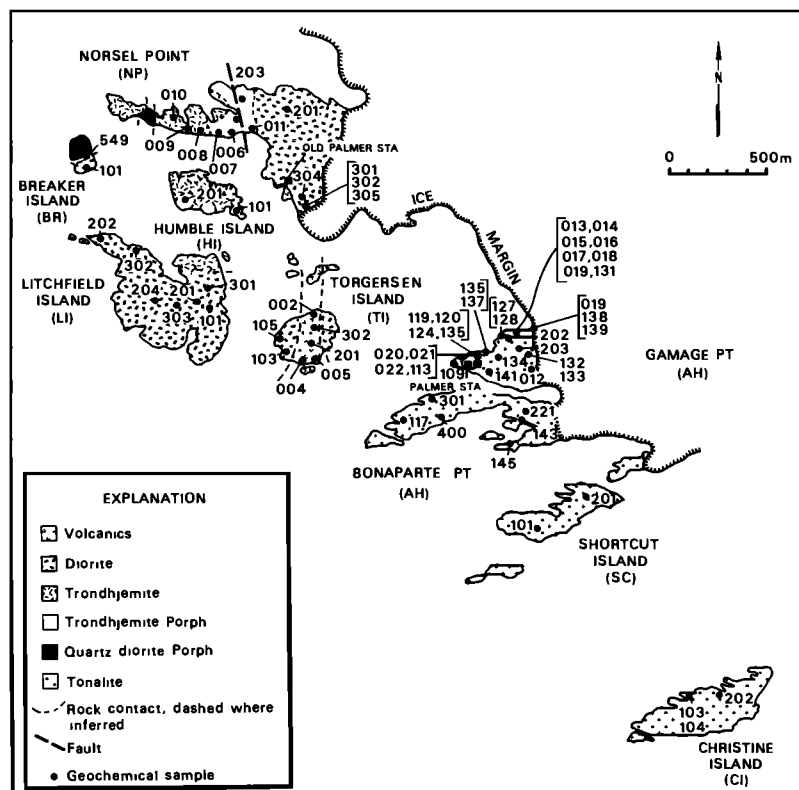


Fig. 5d. Arthur Harbor area. Norsel Point, Gamage Point, Bonaparte Point, and offshore islands. Geology from Hooper [1962] and Moody [1982].

a late stage igneous effect and not related in any way to porphyry-type alteration and mineralization.

The principal region of interest in southwestern Anvers Island was the Arthur Harbor area, including the immediate offshore island (Figure 5d). Except for isolated occurrences, the offshore islands are largely unaltered and unmineralized. A sample of veined tonalite from Christine Island (CI-103, Table 6) is anomalous in copper and gold; samples LI-204 and 302 from Litchfield Island are anomalous in gold and lead, respectively; and several samples carry anomalous silver, most notably, LI-202 and 302 (67 and 14 ppm) from Litchfield Island, SC-101 (75 ppm) from Shortcut Island, and HI-101 (10 ppm) from Humble Island. A small outcrop of volcanic rock on southern Torgersen Island is strongly silicified and stockwork veined with quartz, pyrite, magnetite, and chlorite, and the rock has a "porphyry deposit" look. However, samples TI-103 and 105 from the outcrop contain very low concentrations of the trace metals (Table 6), and the surrounding outcrops are largely unaltered and unmineralized.

Mineralization in the Arthur Harbor area apparently is centered on Gamage Point (Figure 5d). Moody [1982]

described a series of 24 regularly spaced quartz-sulfide veins that are exposed across Gamage Point. The veins strike generally N50°W and dip 47° to 74° southwest. They pinch and swell along strike, the greatest width being about 20 cm. In hand specimen, the veins consist of quartz and pyrite, plus molybdenite, chalcopyrite, arsenopyrite, galena, and sphalerite. Additional minerals noted in polished surfaces from five of the veins include hematite, pyrrhotite, enargite, covellite, and native gold. Obvious alteration selvages to the veins are narrow, persisting only from 2 to 5 cm outward into the tonalite country rock from the margins of the veins. The alteration is "potassic" in nature, characterized by the presence of K-feldspar, quartz, and sericite. According to Moody [1982], weak potassic alteration is present across the entire Gamage Point peninsula, but it becomes extreme only at the margins of the veins.

A small number of quartz-pyrite veins also were examined southwest of Old Palmer Station, southern Norsel Point (Figure 5d). Sphalerite, hematite, chalcopyrite, enargite, and covellite, in order of relative abundance, were identified in polished surfaces of the vein material. The veins range in thickness from 1 to 5

cm, and the country rocks are silicified to about 7 cm outward from the veins.

Table 7 summarizes the distributions of trace elements in the veins from Gamage Point and from the Old Palmer area. Anomalous copper and gold are present in the veins from the Old Palmer area, but the alteration and mineralization are not nearly as significant as on Gamage Point. In all cases, mean trace metal concentrations are higher and ranges are more extreme for samples from the Gamage Point vein system. Of particular note, the highest gold values by far in samples collected during the present study come from this area. Values range to 3100 ppb (3.1 ppm) in sample AH-124, and native gold was identified in a polished surface from this locality. Silver is present in the veins but is not nearly as anomalous as gold, reaching 103 ppm in sample AH-113, which also carries 745 ppb gold. Some samples of tonalite also contain anomalous silver (e.g., AH-109, 117, and 141). Sample AH-141 from Gamage Point appears to be unmineralized, yet it carries 230 ppm silver.

Veins from both Gamage Point and Norsel Point contain molybdenum and tungsten, in addition to anomalous copper, lead, zinc, gold, and silver. The highest concentrations of molybdenum found anywhere during the present investigation are present in the veins on Gamage Point. Samples AH-113 and AH-127, both from near the present Palmer Station, contain 280 and 566 ppm, respectively. Tungsten reaches a maximum concentration of 39 ppm in sample AH-124, from Gamage Point, and scheelite also was identified in this sample.

Minerals such as arsenopyrite, pyrrhotite, molybdenite, and scheelite are indicative of high-temperature mineralization and support the conclusion that the center of mineralization in the Arthur Harbor area is on Gamage Point. Examination of liquid plus vapor fluid inclusions in samples AH-124 and AH-131 yielded filling temperatures that range from 250° to 386°C and 357° to 375°C, respectively, which means that the fluids from which the veins formed were quite warm. In addition, the tonalite on Gamage Point and Bonaparte Point also has been mineralized. Samples often are fractured and stained with iron oxides and copper carbonates, and they contain microveinlets of quartz plus pyrite and chalcopyrite. The mean copper content in eight samples of "mineralized" tonalite is 1298 ppm, compared with 168 ppm for 10 samples of "fresh" tonalite (Table 6). *Moody* [1982] and *Pride and Moody* [1983] concluded that the mineralization on Gamage Point may reflect the presence of a porphyry copper or copper-molybdenum system in the ice-covered area east of the present Palmer Station.

DISCUSSION AND RECOMMENDATIONS

Traces of mineralization are widespread in rocks of the northern Antarctic Peninsula, and similarities in the

geology of the peninsula and the mineral-rich Andes of South America have led researchers to suggest that the Antarctic Peninsula may contain porphyry copper and related base and precious metal deposits. Twenty localities in the South Shetland Islands, the Gerlache Strait, and southern Anvers Island have been examined to evaluate their potential as sites of "Andean-type" mineralization. Mineral occurrences were examined and mapped, and samples were collected for petrographic studies and trace element analysis.

Together with iron (as pyrite), copper, lead, and zinc are present in most of the localities that were visited, and molybdenum, gold, and silver also are important components of the mineralization. This association corresponds to the vein and breccia-hosted Fe + Cu + Zn + Pb + Mo metallogenic association of *Willan* [1987]. Silver is present in concentrations of tens to hundreds of parts per million, and gold is present in concentrations of tens to hundreds of parts per billion at several of the localities that were examined. Native gold was noted in polished surface studies of vein material from Gamage Point, southern Anvers Island, and concentrations of gold in samples from there range to 3100 ppb (3.1 ppm, equivalent to 0.09 ounce of gold per ton of rock).

The following localities, ranked in order of potential interest, have been identified as possible sites of porphyry and related base and precious metal mineralization in the northern Antarctic Peninsula: (1) east of Palmer Station, southwestern Anvers Island; (2) along the coast north of Bahia Frei in the Gerlache Strait; (3) northeast of False Bay, Livingston Island; and (4) north of Johnsons Dock (Hurd Peninsula), Livingston Island.

Additional work is needed to properly evaluate the four localities. Geophysical techniques (gravity, magnetics, electrical methods) and core drilling, as permitted by the Antarctic Minerals Convention (the Convention on the Regulation of Antarctic Mineral Resource Activity, adopted by the Antarctic Treaty Nations in Wellington, New Zealand, June 2, 1988), will be useful additions to the geologic and geochemical studies. For example, the area east of Palmer Station on Anvers Island is covered by ice, and geophysical methods plus drilling through the ice will be needed to adequately assess the resource potential of the area. The locality north of Bahia Frei in the Gerlache Strait also will be difficult to evaluate, but additional study is strongly encouraged on the basis of the intensity of the mineralization present there. *Alarcón et al.* [1976] used helicopters to map the geology and mineralization within the strait, and this may be the only way to gain access to outcrops inland from the coast and to establish stations for geophysical studies.

An extensive zone of iron staining was noted in 1981 in rock outcrops across a highly crevassed glacier in the northeast False Bay area, Livingston Island. The treacherous ice conditions coupled with time limitations

prohibited study at that time, but traverses should be made inland from the coast to map and sample the rock exposures and to establish geophysical stations. In a similar fashion, traverses inland from the coast in the area north of Johnsons Dock might reveal the presence of additional mineralization and/or the presence of the intrusion(s) that apparently spawned the veining exposed there and to the south in the vicinity of Johnsons Dock.

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URANIUM RESOURCE EVALUATION IN ANTARCTICA

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The continent of Antarctica, which comprises roughly 9% of the total land area of the Earth, has been almost totally unexplored for uranium resources. In 1976 the first systematic uranium resource evaluation was started as part of the U.S. Antarctic Research Program. This project has been staffed jointly by scientists from the University of Kansas and the Bundesanstalt für Geowissenschaften und Rohstoffe of the Federal Republic of Germany. The survey continued for ten Antarctic field seasons and included four areas in the Transantarctic Mountains, a part of Marie Byrd Land, the Ellsworth Mountains, and the Antarctic Peninsula. Although it was demonstrated that radiometric surveys could be performed successfully under the rigorous climatic conditions of Antarctica, it was clear that the predictive value of the data was limited by the small number of outcrops. Most outcrops in Antarctica are surrounded by ice, are irregular in areal extent, and frequently show very high relief. For these reasons, it was originally assumed that only ratios of equivalent thorium/equivalent uranium or potassium/equivalent uranium could be reliably determined because these measurements are relatively insensitive to variations in detector-outcrop distance, counting geometry, and partial shielding by intergranular ice or light snow cover. However, from our experience we find that the airborne radiometric data provide a reproducible and essentially accurate measure of the distribution and, within the limits of counting statistics, the absolute abundance of uranium, thorium, and potassium in the outcrops surveyed. Thus far, numerous significant radiation anomalies have been detected and several extensive occurrences of both uranium and thorium minerals have been found. Accumulations of uranium and thorium in pegmatites containing rare Earth elements were also located by the radiometric surveys.

INTRODUCTION

One of the primary objectives of the radiometric survey was to provide a comprehensive assessment of the uranium resource potential of the Antarctic continent. The total area of Antarctica is approximately 13.5×10^6 km², but only about 2% is ice free [Zumberge, 1979]. Rock exposures that are accessible for direct surface or airborne radiometric measurement are distributed mainly along the coastal areas and in the Transantarctic Mountains, where they constitute about 260,000 km². Many of the individual outcrops are widely separated, and large contiguous ice-free areas are not common. The long distances between outcrops, the high relief that characterizes most of the ice-free terrain, the extreme polar climate, and the remoteness from inhabited areas make radiometric survey activities both difficult and costly. Work is limited to the Antarctic summer season with an operational period of about 3 months per year.

In the 10 years that the radiometric survey was in progress, about 218,000 km² of the continental surface

were accessible by helicopter either from land-based campsites or from an icebreaker. Rock exposures varied from less than 5% in Marie Byrd Land to more than 30% in parts of southern Victoria Land. The configuration of flight lines was determined mainly by the terrain, but in areas of high uranium variability more flight lines were added to delineate the extent of anomalous zones. The total flight line distance covered in the combined areas was approximately 30,000 km with a measurement footprint averaging 50 m in width. Therefore direct measurement of radiation was made on a total of about 1500 km² and was used as a basis for evaluation of the 218,000 km² accessible. This means that of the approximately 260,000 km² of actual exposed rock over all of Antarctica, the statistical sample resulting from our flight operations constitutes about 0.6%. We believe that this furnishes a reasonable base of data for evaluating the uranium resource potential of the areas we examined.

The Antarctic continent is conventionally divided into two major sectors that coincide roughly with the bound-

aries of the eastern and western hemispheres. East Antarctica comprises the main mass of the continent, and it includes the old crystalline rocks of the continental shield which are exposed primarily in the coastal regions. The Transantarctic Mountains form a natural boundary along the border between East Antarctica and West Antarctica, and they serve as a barrier to retain the massive East Antarctic ice sheet which covers all but the peripheral areas of that sector. West Antarctica is also covered by ice, but a large portion of its rock surface actually lies below sea level, and outcrops are confined to relatively isolated ranges which project above the ice. In general, the rocks of West Antarctica are younger and show more evidence of Mesozoic and Tertiary tectonic activity than do those of East Antarctica. Thus far, project operations have been divided between survey areas in the Transantarctic Mountains and in West Antarctica. The old rocks of the continental shield have not been directly accessible to the survey.

FLIGHT OPERATION METHODS

Data Acquisition System

The gamma ray spectrometer that was used for this survey consisted of a GAX 512 NaI (Tl) detector with two crystals having a combined volume of 8390 cm³, GR-800A gamma ray spectrometer, and a GAR-6 six-channel analog recorder. Thermal stabilization is provided by a GR-900 interface which also furnishes high-voltage power to the photomultipliers. The analog output in the uranium and potassium channels is corrected for Compton scattering. A more detailed review of survey equipment can be found elsewhere [Zeller and Dreschhoff, 1980; Dreschhoff *et al.*, 1983; Zeller *et al.*, 1982].

Data were collected in the form of strip chart records on the six-channel analog recorder. This practice was a departure from most airborne gamma ray surveys, which make use of digital recording equipment. Although the GR-800A gamma ray spectrometer is capable of this type of output, field conditions and the nature of the Antarctic environment make this mode of operation impractical. First, digital data recording systems do not function well at extremely low temperatures. A heat source might be provided, but the weight and power requirements could adversely affect helicopter operation. Second, the availability of an analog record, which is visible during flight, aided in selecting areas where landings for ground surveys could be made. This was particularly important because return flights to many areas were usually impossible. Third, radar altimeters normally used to furnish digital data about ground clearance are practically useless in the extremely high relief encountered in Antarctica. A large amount of flying took place near cliff faces where vertical-looking radar provides false indications of detector to outcrop

distances. Analog data were converted to digital form in the laboratory by a Tektronix 4052 series graphic computing system. This facility includes a 4052 interactive terminal, a 4956 digitizer, a 4907 disk drive, and a 4662 digital plotter.

System Evaluation

To compare the relative effectiveness of our gamma ray spectrometer and flight operations system with those used by other surveys, we adopted the formula proposed by Darnley [1971]. This formula provides a "figure of merit" which permits comparisons between surveys and takes into account both detector volume and flight operation methods. Using this formula, we found that in locating small radioactive targets, our total survey system exceeds the search effectiveness of very costly large-volume detectors mounted in dedicated fixed-wing aircraft. For large area targets where detection of low-level radioelement enrichments is the primary objective, our survey was slightly more than half as effective as a large detector system. However, the types of surveys over large targets that are commonly made in tropical or temperate regions are impossible in Antarctica because of the small exposure size. For these reasons, we believe that our survey has been conducted with maximum efficiency and with equipment of optimum design for the conditions existing in Antarctica.

The actual precision of measurement is related directly to the count obtained from a section of the flight record, and this, in turn, is determined by detector volume, distance to the ground, and aircraft forward speed. If the aircraft speed is 30 m/s and the average net count rate in the uranium channel (Bi-214) is 6 counts per second, the relative error would be

$$\frac{1}{\sqrt{6}} \times 100\% = \pm 41\%$$

However, in digitizing the analog record, integrations over less than 5 s of flight line data are never used. As a result, the counting error does not exceed

$$\frac{1}{\sqrt{30}} \times 100\% = \pm 18\%$$

which is an acceptable confidence level for an average uranium count. However, in most cases, outcrops were large enough that 15 s of integration are used. On an average, the counting error in most of the data on which the survey is based is approximately $\pm 10\%$.

Calibrated Flight Path

In compliance with International Atomic Energy Agency recommendations, a calibrated flight path was established near McMurdo Station in 1976. This permit-

ted testing and recalibration of airborne apparatus at any time and allowed rechecking in the event of modification or alteration of the equipment. The area of Nussbaum Riegel in Taylor Valley was selected as the site for the establishment of the calibrated flight path [Zeller *et al.*, 1982]. This calibrated flight path was used to check in-flight counter response to known, rapid variations in ground radioactivity over a distance of 4.1 km. Over the period of the survey, we found the counter response could be reproduced with a standard deviation of $\pm 10\%$. In addition, counter response was tested at the Arizona test facility of the Department of Energy. Flights were made in one of the UH-1N helicopters from VXE-6, the Antarctic Development Squadron of the U.S. Navy. The aircraft was flown from the Naval Air Station at Point Mugu, California, for the calibration. The operation was conducted on two consecutive days at 50-, 100-, and 300-foot terrain clearances with differing spectrometer settings. Sensitivity in the potassium channel (1.36–1.56 MeV) was determined to be 41.4 counts/s per 1% potassium; in the uranium channel (1.67–1.87 MeV), 3.6 counts/s per ppm equivalent uranium; and in the thorium channel (2.4–2.8 MeV), 2.3 counts/s per ppm equivalent thorium. The uranium values are measured as Bi-214 and reported as ppm equivalent uranium (eU). Similarly, the thorium values are measured as Tl-208 and reported as ppm equivalent thorium (eTh).

Air Operation and Data Acquisition Techniques

Both the flight operations and the spectrometer system were designed to produce an optimum reconnaissance survey under the constraints of Antarctic field conditions. In all helicopter flights, forward speeds were maintained at about 30 m/s (about 60 knots), and ground clearances were held to between 15 and 30 m. Under normal flight operations on other continents, such low flight would be regarded as unnecessarily hazardous, would degrade search effectiveness, and would require very close line spacing [Darnley, 1971]. In Antarctica, however, the footprint (area of measurement below the detector) is sometimes only slightly smaller than the total outcrop size. In these cases, where scan width was roughly equal to the size of the exposure, the only useful data were obtained by low and slow flight.

Data reliability can be greatly improved by careful monitoring of spectrometer output and Th/U ratios during the flight. Since the terrain made strict adherence to grid flight lines impossible, it was standard practice to confirm immediately, by repeated overflights, every anomaly that was detected. Whenever possible, landings for ground checking of anomalous outcrops were made. This was possible because of the inherent flexibility provided by helicopter operations. Many anomalous readings extended for substantial distances (at least 150 m) along the flight track.

Some characteristics of Antarctic geology contribute to a still further improvement in the quality of our radiometric data. A major problem encountered in making surveys in Antarctica is the fact that outcrops are usually widely separated by intervals of thick snow and ice. While the intervening ice cover limited the amount of outcrops surveyed, it provided a very substantial technical benefit in making radiometric surveys. The large expanses of ice cover provided almost constantly updated information on the level of background radiation reaching the detectors from sources including atmospheric radon and cosmic rays. This eliminated the need for heavy and costly "upward looking" detector crystals which are normally required to provide continuous monitoring of background radiation. When flight records were digitized in the laboratory, this information was incorporated so that changes in background were continuously adjusted to local conditions.

In general, airborne gamma ray surveys are effectively limited to the detection of radioelements only in the uppermost few centimeters of exposed rocks [Saunders and Potts, 1976]. Migration of uranium away from exposed rock surfaces and into the interior of outcrops will reduce the radiation from the uranium decay series that can reach the detectors. This implies that uranium anomalies detected by airborne surveys tend to underestimate actual whole-rock uranium concentration [Saunders, 1980].

Finally, data provided by an airborne gamma ray spectrometer system can be useful in distinguishing rock types by their radiation signatures. Use of this principle is widespread in the petroleum industry, where radiometric logging of sedimentary sequences in bore holes is routine. We tested the technique in the Ellsworth Mountains and found it possible to differentiate stratigraphic units on the basis of their radioelement content [Dreschhoff *et al.*, 1990]. Experience has also shown that igneous bodies often display relatively consistent radioelement distributions that can be used to identify outcrops from the air.

GEOLOGY OF THE SURVEY AREAS

Southern Victoria Land and the Darwin-Byrd Glacier Area

The survey areas in southern Victoria Land (78°30'S–76°40'S) and surrounding the Darwin Glacier and Byrd Glacier (79°S–81°S) in the central Transantarctic Mountains are shown in Figure 1. The radiometric survey was first undertaken in 1976–1977 in southern Victoria Land and continued in 1977–1978, 1980–1981, and 1985–1986. In the 1978–1979 season, operations were conducted from a remote camp on the Darwin Glacier. In both areas the oldest rocks crop out along the coast and consist of a metamorphic complex of gneisses, schists, phyllites, and marbles. These rocks have been named

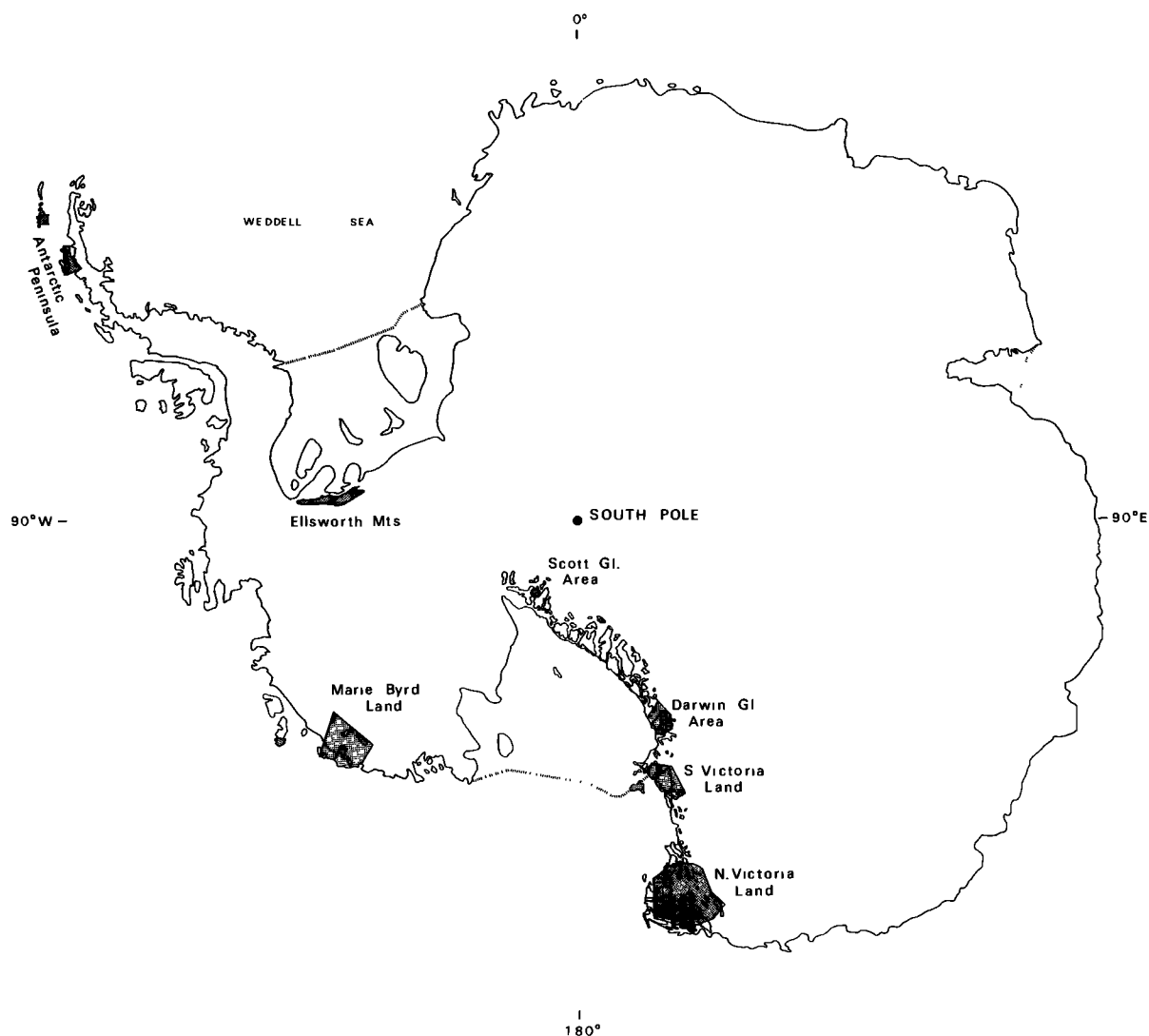


Fig. 1. Map of Antarctica showing the survey areas (northern Victoria Land, southern Victoria Land, Darwin Glacier-Byrd Glacier area, Scott Glacier area, Ellsworth Mountains, Marie Byrd Land, Antarctic Peninsula).

the Ross Supergroup Metasediments, and they range in age from late Proterozoic to upper Cambrian [Grindley and Warren, 1964]. The total thickness of the Ross Supergroup Metasediments is thought to be about 9000 m and they are generally considered to be basin deposits. However, massive limestones and dolomites crop out in southern Victoria Land and in the mountains just south of the Byrd Glacier. The presence of these sediments suggests that some relatively stable shelf areas were developed and that they were maintained long enough to permit accumulation of thick carbonate sequences [Blank *et al.*, 1963].

Deposition of the original sediments was followed by the Ross Orogeny and the emplacement of the Granite

Harbor Intrusives. These igneous bodies have been dated by Rb/Sr whole-rock techniques and provide ages between 450 and 540 m.y. [Borg, 1983; Faure *et al.*, 1979]. During this period of tectonic activity, a number of masses of granite, granodiorite, and diorite were intruded and widespread folding and regional metamorphism occurred. The igneous bodies were designated as the Granite Harbor Intrusives by Gunn and Warren [1962], and they are clearly associated with the metamorphic rocks. A posttectonic phase with true intrusives can be readily separated from the syntectonic phase that consists mainly of gneisses and migmatites. The Larson Granodiorite is syntectonic and has been classified as intrusive largely because it forms a batho-

lithic body nearly 400 km in length parallel to the coast of southern Victoria Land. Actually, it commonly shows gneissic and foliated texture and is probably the product of high-grade metamorphism and partial anatexis. The smaller granitic bodies are undeformed and discordant and they are posttectonic. The complex nature of their relationships is discussed by *Findlay* [1985]. In the Transantarctic Mountains the Hope Granite in the south and the Irizar Granite in the north are examples of these types of intrusives. They are substantially higher in radioactivity than the Larson Granodiorite and its equivalents. Large pegmatite zones occur in several parts of the survey area, and these frequently show elevated radioactivity levels. The lit-par-lit intrusions at Mount Dromedary in southern Victoria Land and the Reeves Bluffs outcrops in the Darwin Glacier area are typical examples of radioactive pegmatites. The geologic ages measured on these metamorphic and igneous rocks range from about 540 to about 450 million years [*Borg*, 1983; *Faure et al.*, 1979].

The Ross Orogeny and the posttectonic intrusive phase were followed by a period of uplift and erosion during which the pre-Beacon erosion surface was developed. The surface was formed in the interval between the end of the Cambrian and the beginning of the Devonian. This surface truncates all of the underlying structures and intrusive bodies and constitutes the most extensive sedimentary hiatus in the Paleozoic sequence. The pre-Beacon erosion surface is of interest because of the discovery of local depressions containing substantial concentrations of thorium minerals, rare Earths, and tin. The depressions range in size from a few hundred meters to over 1 km and are filled with conglomerates and sandstone that comprise the lowermost beds of the Beacon Supergroup [*Zeller and Dreschhoff*, 1980, 1987].

The Beacon Supergroup [*Barrett*, 1971] can be separated into two major divisions, the Taylor Group of Devonian age and the Victoria Group which is Permian-Triassic. Thus far, radioactive minerals have been found only in the base of the Taylor Group. Carbonaceous zones and channel sandstones are common in the Victoria Group, and they should provide ideal geochemical conditions for the accumulation of uranium deposits, but to date, only minor concentrations have been detected. The Beacon Supergroup is overlain in some areas by the Jurassic Kirkpatrick Basalts and is intensively intruded by the Ferrar Dolerites also of Jurassic age.

The last major magmatic event in this portion of the central Transantarctic Mountains was the eruption of a series of highly alkalic volcanic rocks. The volcanism probably began in late Tertiary and was associated with faulting along the Ross Sea margin. It continues to the present time in the activity of Mount Erebus. The extrusive rocks include olivine basalt, phonolite, and trachyte [*Kyle and Treves*, 1973].

Northern Victoria Land

Field work was conducted in northern Victoria Land in the 1981–1982 field season. The geology of the survey area (71°S–74°S) is complex, but for convenience it can be divided into two major districts which are separated by the Rennick Fault [*Dreschhoff et al.*, 1983; *Zeller et al.*, 1986a]. The late Precambrian Robertson Bay Group attains its maximum development in the coastal mountains. In general, this thick sequence of greywackes and turbidites is strongly folded and often intruded by granitic bodies of the Admiralty Intrusives. The Bowers Graben is the major structural feature that dominates the northeastern district. It intersects the Rennick Fault at roughly 30 degrees and can be traced from the Ross Sea south of Cape Hallett to the northernmost outcrops at Rennick Bay. The Bowers Graben contains Cambrian volcanoclastics and sediments. The very strong differences in radioactivity of some members of the Bowers Group make these formations easy to recognize from aerial gamma ray surveys.

The Admiralty Intrusives are present on both sides of the Bowers Graben, and at Gallipoli Heights, the Gallipoli Rhyolite represents an extrusive phase of the Admiralty Intrusives [*Tessensohn et al.*, 1981]. The mineralization associated with the Admiralty Intrusive body at Mount Dockery is clearly accompanied by increased radioactivity, but though it does not appear adequate to produce significant accumulations of uranium minerals, it does merit close reexamination. The pre-Beacon erosion surface and the Beacon Supergroup sediments that lie above it are exposed at a few localities south of the Neall Massif and along the Canham Glacier. Beacon Supergroup sediments are present in drag folds along the southwestern edge of the Lanterman Range.

West of the Rennick Fault, in the Daniels Range, the Wilson Group rocks crop out in extensive exposures at Thompson Spur and Schroeder Spur. They are thought to be the oldest Precambrian rocks in the area. The Granite Harbor Intrusives outcrop in the Emlen Peaks, the Outback Nunataks, Frontier Mountain, and the Caudal Hills and Lichen Hills. Many outcrops show very large radioactive pegmatite bodies containing prominent smoky quartz crystals. The areas of outcrop of the Granite Harbor Intrusives, especially those showing massive pegmatites as at Frontier Mountain and Mount Bower, have the highest uranium resource potential in northern Victoria Land. The pre-Beacon erosion surface which truncates the Precambrian metamorphics and the Granite Harbor Intrusives can be found from the Morozumi Range on the north to the Caudal Hills and Lichen Hills on the south. Beacon Supergroup sediments are present over much of the southwestern district, and they are extensively intruded by the Ferrar Dolerites. Tertiary and Quaternary volcanics outcrop at Mount Overlord and along the coast in the Hallett Volcanic Series.

TABLE 1. Median Aerial Radiometric Data for Six Survey Areas in Antarctica

Survey Area	eU,* ppm	eTh,* ppm	K,* %	Number of Significant eU Anomalies	eU Anomalies Identified in Figure 2
Northern Victoria Land	2.56	8.98	1.23	3	Mount Bower (1) Lichen Hills (2) Everett Spur (3)
Southern Victoria Land	2.97	8.04	1.70	8	The Bulwark (1) Roaring Valley (2, 3) Mount Dromedary (4, 5) The Pyramid (6) Pyramid Trough (7) Granite Harbor (8)
Darwin Glacier- Byrd Glacier	1.27	5.51	0.96	9	Brown Hills (1-6) East of Reeves Bluffs (7, 8) Zeller Glacier (9)
Ellsworth Mountains	1.65	5.91	0.90	2	Founders Peaks (1) Founders Escarpment (2)
Marie Byrd Land	3.94	5.90	1.24	2	Bailey Nunatak (1) Billy Bluff (Ickes Mountains) (2)
Antarctic Peninsula	0.83	2.48	0.54	0	
Antarctica	2.09	6.56	1.12		

*eU, uranium measured as Bi-214; eTh, thorium measured as Tl-208; K, potassium measured as K-40.

Upper Scott Glacier Area

Pegmatites had been found to contain small occurrences of both primary and secondary radioactive minerals at locations along the upper Scott Glacier, which is located in the southernmost Transantarctic Mountains (86°30'S) (E. Stump, personal communication, 1982). A short airborne radiometric survey over these outcrops was conducted by mounting our gamma ray spectrometer in an LC-130 aircraft. This traverse confirmed the existence of radiometric anomalies at Szabo Bluff and some of the surrounding areas. A detailed ground examination was made of pegmatite bodies outcropping at Szabo Bluff during the 1982-1983 field season. At this location the pegmatites are thought to be associated with the Granite Harbor Intrusives. Samples of the radioactive minerals from the pegmatite bodies were collected, but the pegmatites were found to be of very limited areal extent. The remoteness of this portion of the Transantarctic Mountains and the lack of helicopter support made a comprehensive examination of the area impossible. Nevertheless, we can extend substantially the known occurrence of uranium-bearing pegmatites associated with the Granite Harbor Intrusives for 1800 km along the Transantarctic Mountains.

Marie Byrd Land

The geology of Marie Byrd Land (142°W-125°W) is much less well known than that of the Transantarctic

Mountains [Wade, 1970]. Exposures are very limited, and the high precipitation rate coupled with the frequent occurrences of severe storms makes flight operations unusually difficult. The dark gneisses and schists that crop out at Cape Burks on the Hobbs Coast are probably the oldest rocks in the area, but their age has not been determined. Small outcrops of arenaceous sediments containing plant fragments were found in 1977 in the nunataks on the Ruppert Coast in the western portion of the survey area. These beds are probably age equivalents of the Beacon Supergroup in the Transantarctic Mountains. Felsic intrusive rocks of Cretaceous age occur at a number of localities, and pegmatites and aplites associated with these rocks show unusually elevated radioactivity levels. The youngest rocks in the area are Cenozoic volcanics that make up the Flood Range and Executive Committee Range. Fumarolic activity continues at Mount Berlin, suggesting that these volcanoes may have been active in the recent past. All radioactive survey activities were conducted during the 1977-1978 field season. The average radioactivity of the rocks in this portion of Marie Byrd Land is substantially higher than that of any of the other survey areas (see Table 1).

Ellsworth Mountains

The airborne radiometric survey in the Ellsworth Mountains (80°45'S-87°S) was undertaken in the 1979-

1980 field season. The field camp was located at the north end of the Heritage Range and provided excellent access to both the Heritage Range and Sentinel Range which make up the Ellsworth Mountains. The survey area is roughly 300 km in length and 60 km in width. Outcrops were limited in the region, which receives over 50 cm of snow each year, and they are generally confined to steep slopes, ridge crests, and a few areas where high winds tend to sweep the rock surfaces free of snow. Several small dry valleys exist in the Heritage Range, but they are of limited areal extent.

Most of the surveyed rocks were sedimentary, but several limited outcrops of basic igneous rocks were also examined. The sediments range in age from Cambrian to Permian (G. F. Webers, personal communication, 1988). The airborne survey track was flown mainly over Cambrian and lower Paleozoic sediments because these outcrops were most readily accessible from the camp location. Two flights did make traverses over upper Paleozoic sediments, but in both cases the outcrops were near the end of the helicopter range and flight time was limited.

In the Heritage Range the Cambrian sediments consist of contorted argillites, phyllites, marbles, sandstones, and shales with a few breccia bodies associated with marbles. The Devonian rocks also show low-grade metamorphism and are tightly folded in many localities. Quartzite is the most common rock type, but some outcrops exhibit fairly extensive interbedding with phyllites, and a few are nearly unmetamorphosed sandstones and shales. Shallow water sedimentary structures occur frequently in many portions of the sedimentary sequence. In the Permian, some thin coal beds are also present. Most of the rocks exposed in the Ellsworth Mountains show evidence of low-grade metamorphism.

The Antarctic Peninsula

The area examined in the Antarctic Peninsula in February and March 1984 included Livingston Island and Deception Island of the South Shetland Islands and the Gerlache Strait and Anvers Island (60°S–63°30'S). Operations were conducted by helicopter from an icebreaker. Rocks ranging in age from Paleozoic to Recent volcanics at Deception Island were surveyed. The Andean intrusives and contact metamorphic zones associated with them provide the only observed possibilities for accumulation of radioactive elements. Sulfide minerals frequently occur in the contact zones with pyrite, chalcopyrite, and molybdenite associations present on Anvers Island near Palmer Station. The zones that show sulfide mineralization appear to be associated with elevated levels of radioactivity at a number of localities, but there is little evidence that they are likely to form significant uranium deposits.

URANIUM PROVINCES

Possible Origin of Uranium Provinces

Previous studies have led to the conclusion that the presence of relatively large amounts of uranium in uraniferous provinces provides a reservoir of intergranular or otherwise leachable uranium that can be transported in solution. Local departures from normal regional Th/U or K/U that are visible in airborne gamma ray survey data are assumed to indicate that leaching has been active and that part of the uranium has been removed. If suitable geochemical conditions exist, the uranium may be transported only a relatively short distance and concentrations in host rock "traps" can occur. This type of mechanism will be significant only if the Earth's crust contains broad scale inhomogeneities in uranium content which are of early origin, as has been suggested by several investigators [Klepper and Wyant, 1957; Bowie, 1977; Robertson *et al.*, 1978].

Chemically reducing conditions are hypothesized to have been prevalent both at depth and in the atmosphere, early in the Earth's history [Cloud, 1976; Dimroth and Kimberly, 1976; Robertson *et al.*, 1978]. Under these conditions, uranium and thorium were both in the +4 valence state [Adams *et al.*, 1959; Gabelman, 1977; Rogers *et al.*, 1978]. Only when chemically oxidizing conditions became well established, probably in the Lower Proterozoic, could uranium readily enter the highly soluble +6 valence state. This increase in mobility permitted uranium to be separated from thorium with the attendant development of a variety of epigenetic uranium deposits. Since thorium is relatively immobile during oxidative weathering processes, the regional distribution of thorium should reflect any original crustal inhomogeneities in uranium content better than does the present uranium content. The origin of the original crustal inhomogeneities is obscure.

Characteristics of Uraniferous Provinces

Klepper and Wyant [1957] pointed out that most of the world's important uranium deposits are clustered in a relatively few areas and suggested that these represent uranium-rich portions of the originally inhomogeneous crust. They also observed that uranium provinces appear to persist through long periods of geologic time, with the uranium being moved from one type of deposit to another within each province by normal erosional, sedimentary, or igneous processes. These provinces are characterized by higher than normal quantities of uranium in all of the rocks and waters [Everhart, 1958; Scott and Barker, 1958; Darnley, 1973; International Atomic Energy Agency, 1977], as well as by the presence of different types of uranium deposits [Dodson, 1972]. Airborne gamma ray spectrometry is the most effective method for detection of uraniferous provinces,

and this technique has been extensively applied in the U.S. Department of Energy National Uranium Resource Evaluation program [Dodd, 1976; Saunders and Potts, 1976; Saunders, 1979] and in the Canadian Federal-Provincial Uranium Reconnaissance Program [Darnley *et al.*, 1975].

Saunders [1979] stated that uraniferous provinces can also be identified by generally high thorium and potassium contents as evidenced by the high degree of correlation between these elements and the uranium content of the rocks. However, if actual uranium ore deposits are present, median eTh/eU ratios in the surrounding areas may be significantly higher. This occurs because the less mobile thorium and potassium will be left behind if the geochemically mobile uranium has been depleted from portions of the area and concentrated in the ore bodies. In general, within the borders of a uraniferous province, the existence of local areas of uranium depletion must be viewed as indicating that uranium mobilization processes have been active and that potential ore deposits may exist. In fact, uraniferous provinces are often characterized by a high degree of variability in the eTh/eU and K/eU ratios, whereas rocks outside the uraniferous provinces show no such variability.

RESULTS OF THE STUDY

Data Processing and Display of Results

The data gathered by the airborne gamma ray survey can be evaluated in a number of ways. Isorad maps are commonly prepared in which the area is contoured on the basis of the radiation reaching the detector from points on a grid covering the map area. In Antarctica the high relief and extensive snow and ice cover resulted in irregular flight line distribution, and contouring accuracy varied markedly from point to point on the map. Therefore in addition to the maps, an alternative method of statistical treatment and data representation similar to a technique used successfully in Alaska by Saunders [1980] was chosen.

In order to accomplish this task, the data were screened to remove values that were not considered to be representative of normal flight operation. Data obtained during extremely low or slow flight and during periods of high turbulence and all measurements made during helicopter hovering operations were rejected. Those portions of the flight path where appreciable signal attenuation could be expected because of partial snow cover were also eliminated. Rejection of data was based on notes made during flight on the recorder output and amounted to less than 0.5% of the total flight record.

Statistical Evaluation and Comparison of Survey Areas

Simple scatter diagrams provide the best graphical representations of the data and allow rapid visual selec-

tion of anomalous values from specific outcrops. Each data point shown in the scatter diagrams in Figure 2 is derived from the gamma ray record of the flight track over an outcrop which can vary from a minimum of about 5 individual data points on the flight record of the gamma ray spectrometer to a maximum of roughly 100 individual data points from the flight record. In each survey area a set of means was calculated for eU, eTh, and K as listed in Table 1. The means serve as standards with which each individual outcrop can be compared. The values have been adjusted by dividing each outcrop value by the overall mean for each survey area for each of the radioelements, of which AU and ATh are presented here:

$$AU = eU/eU \text{ survey area}$$

$$ATh = eTh/eTh \text{ survey area}$$

This results in a set of dimensionless values which indicate their relative deviation from the line where $ATh = AU$. In general, the distance that a point lies from the line can be considered as a measure of the degree of geochemical separation between uranium and thorium in the specific survey area.

The scatter diagrams shown in Figure 2 also include the regression line for the point scatter from each of the survey areas. In these diagrams the regression line is determined by statistical factors. On the other hand, the $ATh = AU$ line represents the average geochemical distribution of thorium and uranium in the rock outcrops that were surveyed. In general, the more these two lines deviate from each other, the more geochemical separation of uranium from thorium that has occurred. Similarly, the lower the slope of the regression line, relative to the slope of the $ATh = AU$ line, the greater the level of uranium enrichment and consequently the greater its geochemical mobility in the specific survey area. Figure 2 indicates clearly that major differences exist among all of the six areas that were investigated by the helicopter survey. At the same time, the three parts of the Transantarctic Mountains (northern Victoria Land, southern Victoria Land, and the Darwin Glacier area) all show certain similarities in point distribution patterns. In fact, the greatest deviation of points from the $ATh = AU$ line is to be found in the Transantarctic Mountains. In Marie Byrd Land the regression line and the $ATh = AU$ line coincide, indicating that in spite of the high average concentrations of radioelements, very little geochemical mobility has occurred.

Table 1 shows that the average uranium and thorium abundances differ for all six survey areas. Concentration means of K, eU, and eTh are presented, but no attempt has been made to prepare separate averages on the basis of specific geologic formations that contribute to the overall mean of each region. Mean concentration values provide the primary basis to determine which outcrops in each individual survey area represent sta-

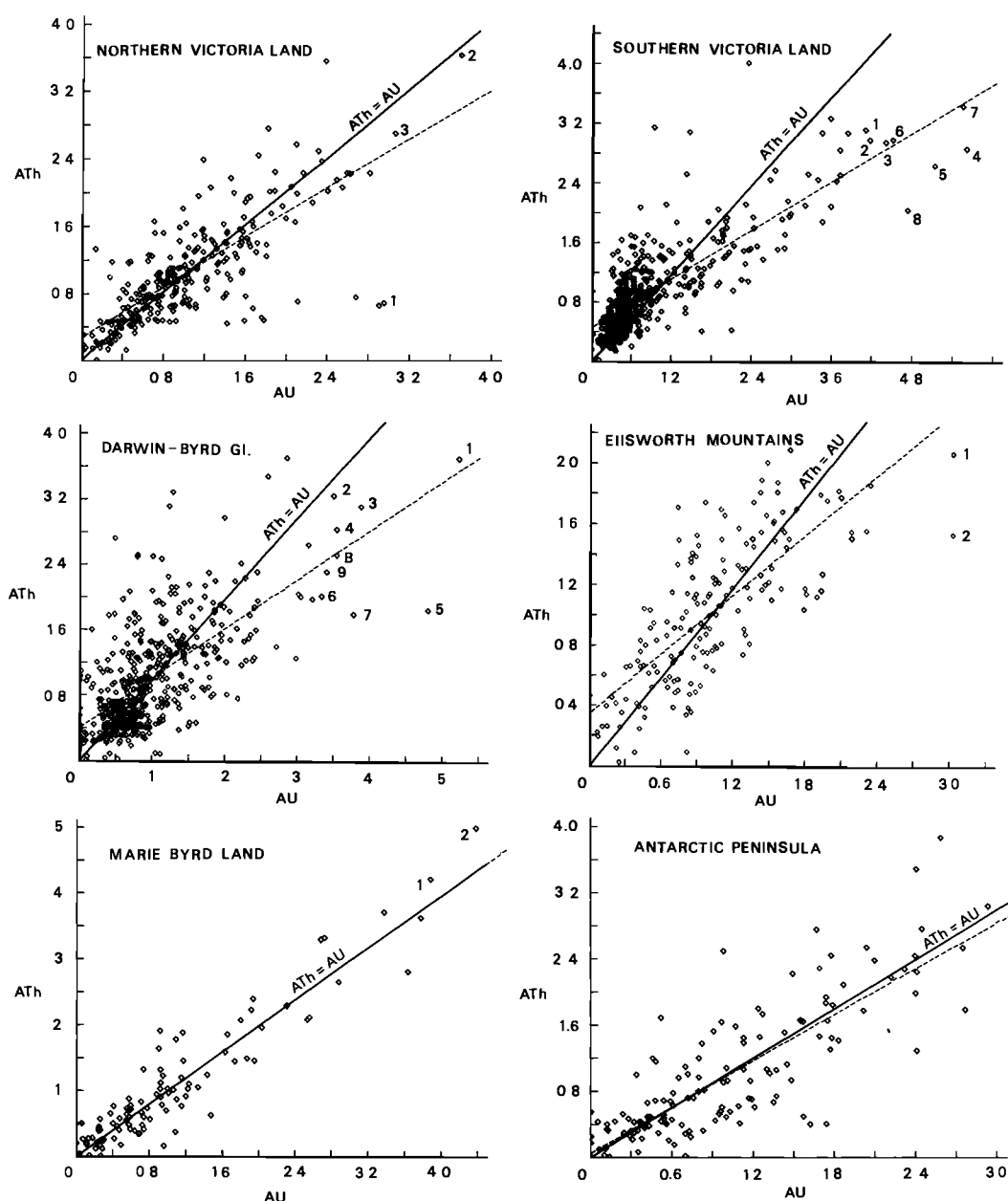


Fig. 2. Scatter diagrams for each of the six areas, which were investigated by airborne helicopter surveys. Each diagram includes all of the outcrops measured in the specific area. A linear regression has been fitted to the data points (dashed line). The adjusted values AU and ATh for each area are related to the corresponding area mean resulting in $AU = ATh = 1$. The solid line runs through the origin and $AU = ATh = 1$. Significant eU anomalies are numbered and identified in Table 1.

tistically significant uranium anomalies. We have defined significant uranium anomalies within each survey area as those that exceed the average uranium concentration for the survey area by 3 standard deviations. All of the significant eU anomalies identified in the scatter diagrams are listed in Table 1. It is important to note that the total number of significant anomalies alone is

not indicative of the uranium resource potential of a survey area but must be considered in combination with the average uranium concentrations.

In northern Victoria Land, three significant uranium anomalies have been located. One of these is associated with the pre-Beacon erosion surface in the Lichen Hills, and the other occurs in basal Beacon Group sediments

resting on the pre-Beacon surface which is developed on the uranium-enriched Granite Harbor plutons at Mount Bower in the Outback Nunataks. The Mount Bower anomaly is characterized by an unusually high eU/eTh ratio. A significant anomaly also occurs at Everett Spur on the Lillie Glacier near Mount Dockery. This anomaly appears to be related to primary mineralization in veins associated with one of the Admiralty Intrusive bodies. Smaller anomalies between 2 and 3 standard deviations from the mean occur in volcanic rocks near Mount Overlord at the Co-pilot Glacier, at several localities on the pre-Beacon erosion surface in both the Caudal Hills and Lichen Hills, in massive pegmatite veins at Frontier Mountain, and in other parts of the Mount Dockery intrusive.

In southern Victoria Land a total of eight significant uranium anomalies have been found. One complex anomaly is present in the granite cliffs that flank the north side of the Mackay Glacier west of the Kar Plateau at Granite Harbor. At this locality, breccia zones associated with veins of red and yellowish colors were found to be high in radioelement concentration. The anomaly extends upstream along the Mackay Glacier for at least 4 km. The other significant anomalies are associated with the granitic terrains in the southern part of the area just north of the Koettlitz Glacier. They occur at The Pyramid, Pyramid Trough, The Bullwark, in Roaring Valley, and on the slopes of Mount Dromedary in the lit-par-lit intrusive series.

In the Darwin Glacier-Byrd Glacier area, nine significant uranium anomalies occur and seven of these are associated with the pre-Beacon erosion surface in the Brown Hills and along the divide between the east and west forks of the Zeller Glacier south of the Byrd Névé. Two significant uranium anomalies were found in pegmatites at small nunataks that are located east of Reeves Bluffs. Smaller anomalies are associated with old metasediments along the Sefton Glacier near Mount Rainbow. Smaller anomalies also occur in the Britannia Range on the north side of the Byrd Glacier between Mount Rummage and the Merrick Glacier. In the Brown Hills, samples of the basal conglomerate of the Beacon Supergroup, which were designated AIRS-1, have been found to contain 0.1–0.3% thorium.

Only two significant anomalies were found in the Ellsworth Mountains, and both were associated with quartzites of lower Paleozoic age. The extremely low average radioactivity of the rocks combined with the uniformly low variability in radioelement concentration in the Ellsworth Mountains suggests that the uranium resource potential is also low. On the other hand, in Marie Byrd Land two significant anomalies were found in granitic intrusives at Bailey Nunatak and Billey Bluff in the Ickes Mountains. Throughout this portion of Marie Byrd Land, the granites appear to show unusually high levels of radioelements, but the scatter diagram

shows little evidence that geochemical processes that could cause separation and concentration of uranium have been active.

No significant uranium anomalies more than 3 standard deviations above the mean were found in the Antarctic Peninsula. However, a total of eight uranium anomalies over 2 standard deviations above the mean were identified. All of these anomalies were associated with veins on Anvers Island and in the vicinity of Paradise Harbor on the Danco Coast.

Maps of Radioelement Distribution

Three of the seven survey areas show a substantial number of significant anomalies. Radioelement anomaly maps have been prepared for northern Victoria Land [Zeller *et al.*, 1986a], and we include here maps for the Darwin Glacier-Byrd Glacier area (Figures 4 and 5) and southern Victoria Land (Figures 7 and 8). The maps are contoured on the basis of one as the mean concentration of uranium or thorium for each entire area. Additional contours are indicated for regions showing 2 to 6 times the mean. As was indicated previously [Zeller *et al.*, 1986a], the statistical reliability of the contour positions on the maps is directly dependent upon flight line spacing. Actual flight lines are plotted on maps of the Darwin Glacier-Byrd Glacier area (Figure 3) and southern Victoria Land (Figure 6).

In the Darwin Glacier-Byrd Glacier area the largest anomalies occur in the Brown Hills. This district is adjacent to the Hillary Coast and is bounded on the south by the Darwin Glacier and on the west by the Touchdown Glacier and Reeves Bluffs. The basement complex of Late Precambrian or Cambrian age consists of folded metasediments including phyllites, schists, gneisses, and metagreywackes with several granodiorite and granite intrusive bodies. The plutons are especially well exposed in this area. The map shows the occurrence of the highest average uranium and thorium content in the exposed plutons, and it indicates a slight enrichment in uranium relative to thorium. This is particularly interesting because it is the only district that contains local accumulations of thorium minerals. These concentrations take two forms. Some of the Hope Granite plutons have elevated thorium levels, and there are significant concentrations in the conglomerates on the pre-Beacon erosion surface. The Hope Granite is not widely distributed over the area, and it is not uniformly thoriferous even where it is present.

Other anomalies in the Darwin Glacier-Byrd Glacier area are associated with Tentacle Ridge, Finger Ridges, and Butcher Ridge. This district extends from the west side of Butcher Ridge, which bounds the polar plateau, across the Finger Ridges to Mount Gudmundson on the east and is elongated to include Tentacle Ridge on the south. The polar plateau and the Darwin Glacier form

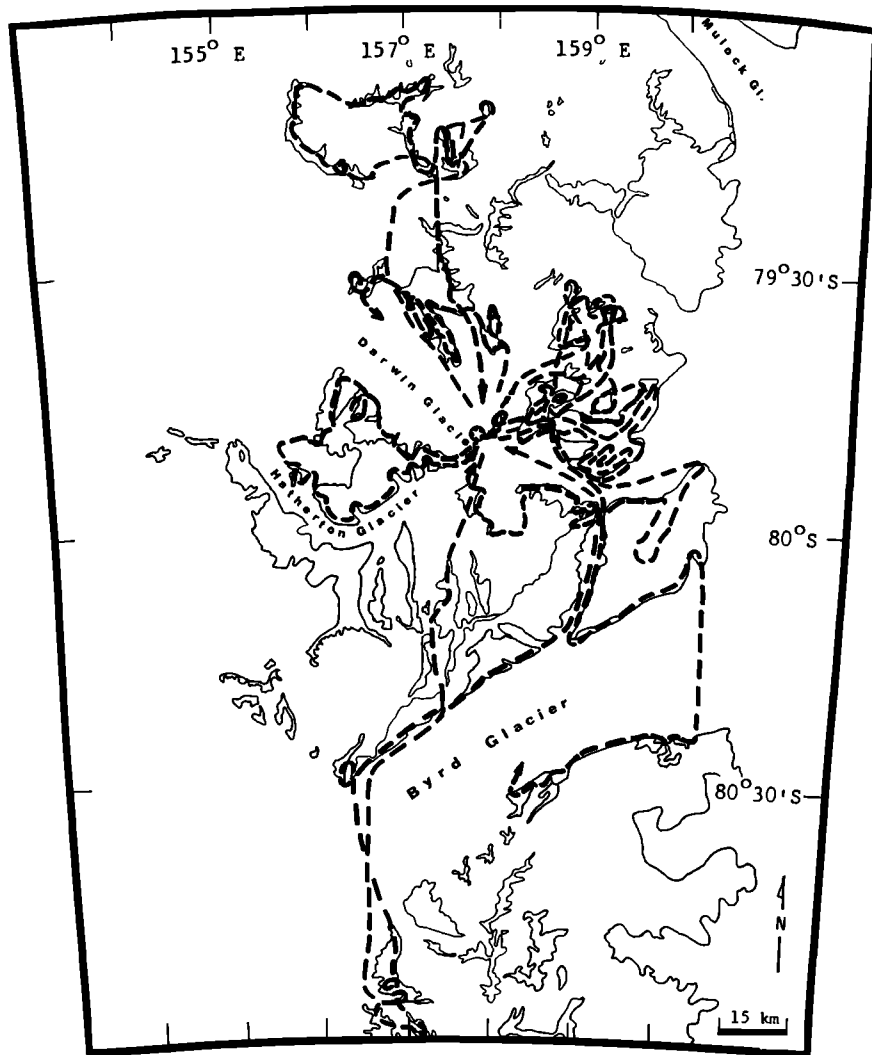


Fig. 3. Map showing flight paths in the Darwin Glacier-Byrd Glacier area.

the southwestern boundary. The basement complex is exposed in a single outcrop about 3 km in length at the north end of Tentacle Ridge. A single rock sample from this outcrop shows over 200 ppm uranium with less than 5 ppm thorium. However, the average concentrations of both uranium and thorium are too low to suggest that substantial deposits of uranium minerals should be expected. The remainder of the Tentacle Ridge area is characterized by outcrops of the lower portion of the Beacon Supergroup sediments and the intrusions of the Ferrar Dolerites. The Finger Ridges to the north are largely composed of Upper Beacon Supergroup sediments and show numerous argillaceous zones with local coal beds. Occasional variegated shales with red and green coloring are present. Although the southern end of Butcher Ridge is clearly made up of Ferrar Dolerite,

the northern half of the ridge consists of dark, layered igneous rocks, some of which show steeply dipping and locally contorted structure.

Only a few scattered low-level uranium anomalies were encountered in the Darwin Mountains. The Darwin Mountains lie between the Darwin Glacier on the north and the Hatherton Glacier on the south. Their western boundary is formed by the polar plateau. The entire district consists of outcrops of Beacon Supergroup sediments and Ferrar Dolerite intrusions. Most of the sediments are thought to be Lower Beacon Supergroup and are probably of Devonian age. At a few locations, shales and tillites were examined. Although there is local evidence of faulting, the beds are generally horizontal or gently dipping.

North of the Byrd Glacier the survey extended from

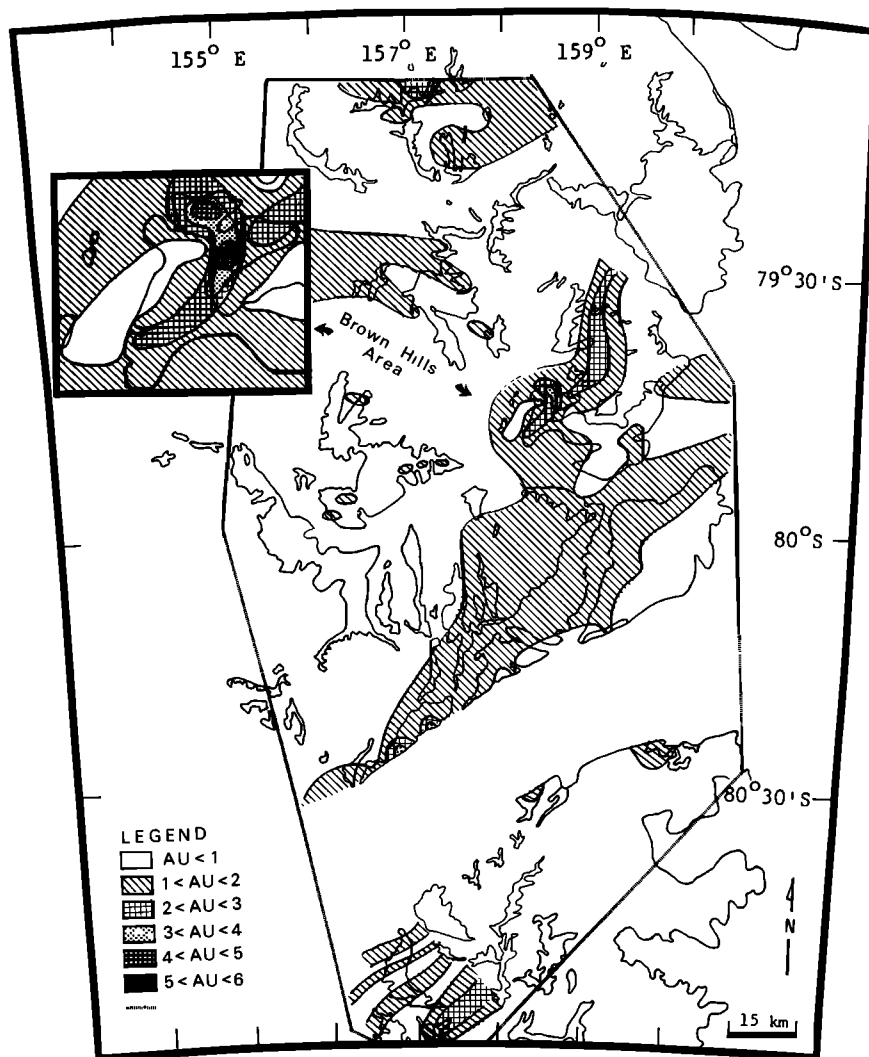


Fig. 4. Map of uranium distribution in the Darwin Glacier-Byrd Glacier survey area. The uranium has been contoured in dimensionless units using adjusted values based on deviations from the area mean ($AU = eU/eU$ survey area).

MacDonald Point on the Hillary Coast to Mount Rummage just east of the Byrd Név. It includes the area between the Darwin Glacier on the north and the Byrd Glacier on the south to the confluence of the Darwin Glacier with the Hatherton Glacier. Most of the rocks examined are part of the basement complex and appear to be metasediments. Near the coast, the rocks show only low-grade metamorphism, but farther inland, much of the original structure appears to be lost and some plutons are present. The high mountains near the head of the Byrd Glacier are capped with Beacon Supergroup sediments intruded by dolerite dikes and sills. The outcrops just north of the Byrd Glacier show an average radioelement concentration that is close to the area

mean, but uranium and thorium anomalies of small areal extent have been found. The anomalies are shown in the maps in Figures 4 and 5.

The rocks that crop out along the south side of the Byrd Glacier from Cape Selborne on the Shackleton Coast to Mount Fries just south of the Byrd Név make up the survey area south of the Byrd Glacier. Nearest Cape Selborne, these rocks are marbles and phyllites, but marble predominates at Mount Tuatara. Granitic plutons are not prominent in this district. Highly contorted metasediments consisting of argillite, phyllite, and dolomitic marble are present at Mount Rainbow, and these rocks are overlain by massive conglomerates where the pre-Beacon erosion surface is exposed at the

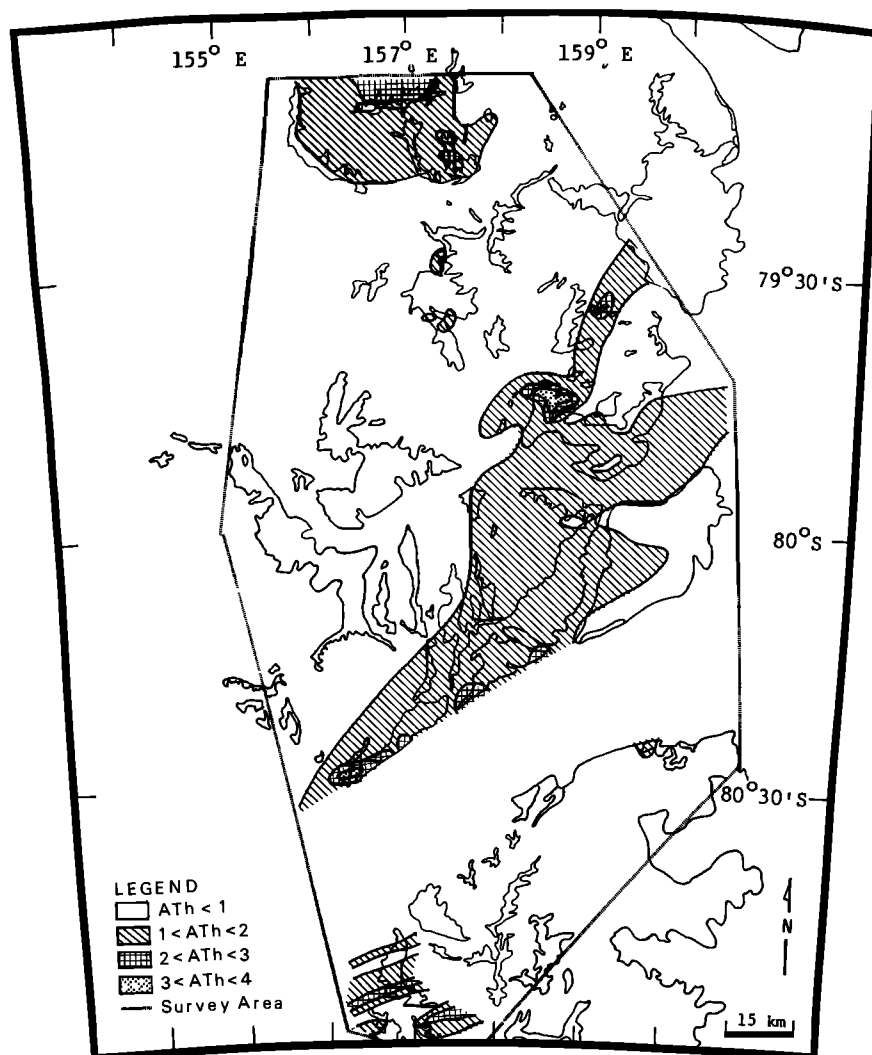


Fig. 5. Map of thorium distribution in the Darwin Glacier-Byrd Glacier survey area. The thorium has been contoured in dimensionless units using adjusted values based on deviations from the area mean ($ATH = eTh/eTh$ survey area).

fork in the Zeller Glacier at the southernmost boundary of the district. Some uranium concentrations associated with the pre-Beacon erosion surface are exposed at the Zeller Glacier. In contrast, in southern Victoria Land, only very small radiation anomalies have been found to be associated with the Kukri erosion surface.

Figure 6 is a map of the survey area in southern Victoria Land. The uranium and thorium anomaly maps of southern Victoria Land are shown in Figures 7 and 8. The uranium anomalies at Granite Harbor and in the Pyramid Trough area show the highest uranium resource potential among all of the survey areas. The discovery of actual accumulations of uranium minerals over an area of 75 to 100 km² from The Pyramid to Roaring Valley provides ample evidence that geochem-

ical processes were active which could have produced substantial local concentrations of uranium. Specifically, the region from the Skelton Glacier to Cape Ross north of Granite Harbor and the area adjoining the Koettlitz Glacier on the north show higher than average levels of radioactivity and higher degrees of variability as well as a greater frequency of anomalous concentrations of uranium than other portions of Antarctica. The similarity in character of the radiometric signature of the two anomalous areas at Pyramid Trough and Granite Harbor suggests that they both merit detailed examination including high-resolution airborne surveys and detailed ground mapping. Ground examinations carried out by our group during survey operations conducted in 1977 near Granite Harbor showed the presence of

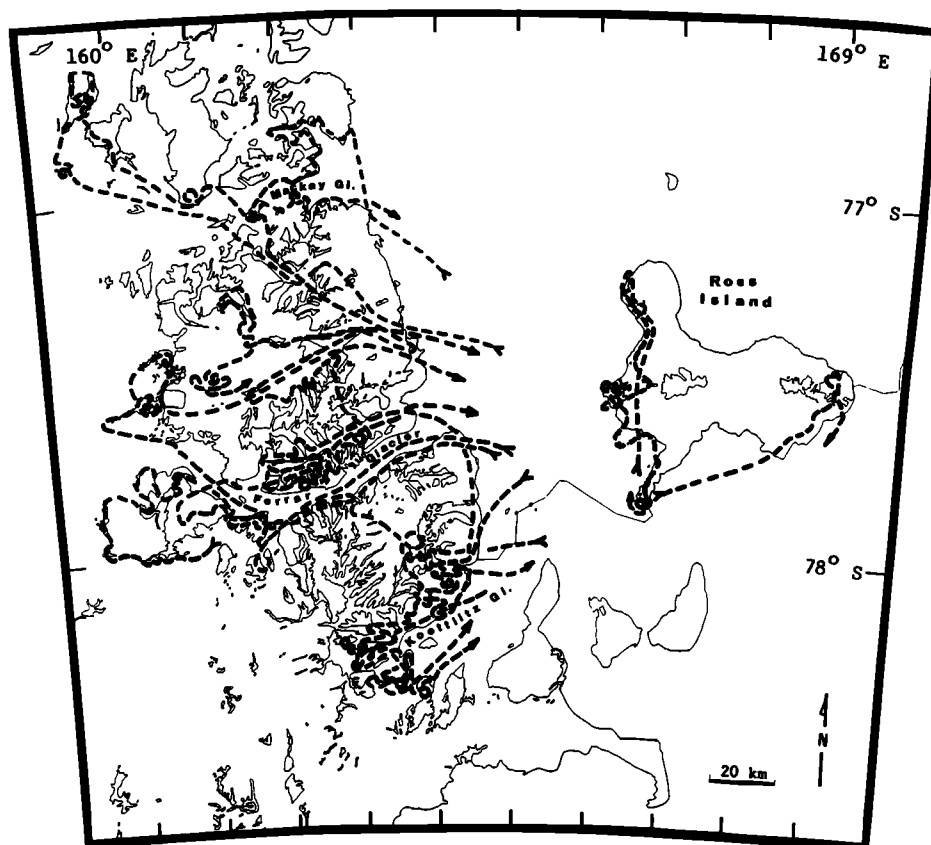


Fig. 6. Map showing flight paths in the survey area of southern Victoria Land.

radioactive veins which were similar in character and areal extent to those occurring in Roaring Valley. Unfortunately, we were unable to return to these localities and sampling was incomplete.

URANIUM ENRICHMENTS ASSOCIATED WITH THE GRANITE HARBOR INTRUSIVES IN SOUTHERN VICTORIA LAND

Discovery of Radiation Anomalies Associated With the Granite Harbor Intrusives

Anomalous radioactivity was first detected in southern Victoria Land in 1976 during the first year of our resource and radioactivity survey in Antarctica. Although at that time we were not equipped with a gamma ray spectrometer and only total gamma ray counting was possible, we recognized that the southern end of the Royal Society Range showed outcrops of highly radioactive rocks. In the following seasons a gamma ray spectrometer was available for airborne operations, and detailed determinations of anomalous uranium concentrations were made in this area. In the 1985–1986 field season a major effort was centered on the area of The Pyramid and the Pyramid Trough which lie just north of

the Koettlitz Glacier. At this location a number of strong anomalies associated with radioactive veins had been detected by flight operations in the early part of the season. The veins were found to be very extensive, and one anomalous zone was discovered that extended along the south wall of Pyramid Trough for over 1 km.

The position recovery technique that is used in our airborne survey operations permits us to locate an airborne anomaly on the ground within approximately 15 m. During subsequent examination of some of the anomalies detected in flight, we were able to walk directly to the outcrop designated AIRS-2. Examination of this outcrop on the Koettlitz Glacier and another pegmatite vein, AIRS-3 at the head of the Pyramid Trough, revealed the presence of both primary and secondary uranium minerals associated with thorium-bearing pegmatites. Photographs and autoradiographs from polished surfaces of radioactive samples collected at AIRS-2 and AIRS-3 are shown in Figures 9 and 10. Uranium analyses performed on hand specimens by neutron activation indicate a concentration of 0.12% uranium in a composite sample from the veins at AIRS-2 and AIRS-3. High levels of thorium are also present.

During flight operations, increases in total radiation

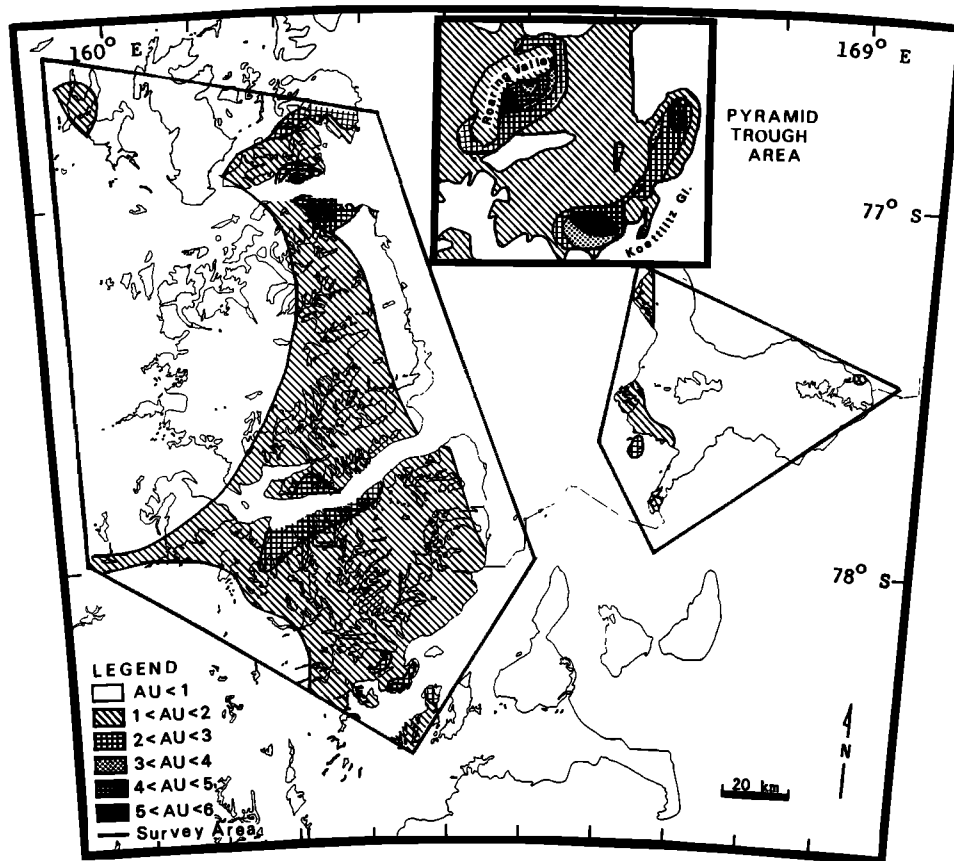


Fig. 7. Map of uranium distribution in the survey area of southern Victoria Land. The uranium has been contoured in dimensionless units using adjusted values based on deviations from the area mean ($AU = eU/eU$ survey area).

background by as much as 24 were observed. On the ground, increases in radiation background derived from the uranium decay series were found to exceed factors of 10 at a number of localities where the radioactive veins outcrop. Some veins contained large amounts of thorium as indicated by increases in background from the thorium decay series by factors of over 20. Incrustations of yellow secondary uranium minerals were found in the highly radioactive vein at AIRS-3. These minerals together with the strongly fluorescent coatings of carbonate minerals containing uranium (see Figure 11) were very widely distributed in fractures extending inward from outcrop surfaces. They furnish clear evidence of mobilization of uranium in solution in the surface weathering zone. At least four uranium minerals are present.

The deceptively fresh and unweathered appearance of many rock outcrops in Antarctica can lead to the conclusion that chemical weathering processes are strongly inhibited, but careful studies have shown that this is not the case [Ugolini and Jackson, 1982]. Furthermore, unexpectedly high levels of oxidation must be

assumed to account for the extensive deposition of secondary uranium minerals in outcrops that we examined in Pyramid Trough in southern Victoria Land. The abundant secondary uranium mineralization discovered during the 1985–1986 field season provides unequivocal evidence that uranium can be removed from outcrop surfaces and transported inward along fractures to a depth of at least 40 cm. In Antarctica the chemical agents that we consider to be responsible for uranium transport are nitric acid (HNO_3), which is present in Antarctic snow and ice [Wada *et al.*, 1981; Zeller *et al.*, 1986b; McElroy *et al.*, 1988], and hydrogen peroxide (H_2O_2), which has also been detected as one of the major trace constituents in Antarctic snow [Neftel *et al.*, 1986]. Both of these compounds occur in snow at average concentrations of approximately 25 ppb each. Although concentrations are low, the integrated total flux of these compounds over the length of time that outcrop surfaces are exposed in Antarctica is probably adequate to produce major chemical effects because they are among the strongest naturally occurring oxidizers. The effects of nitric acid reactions on exposures of

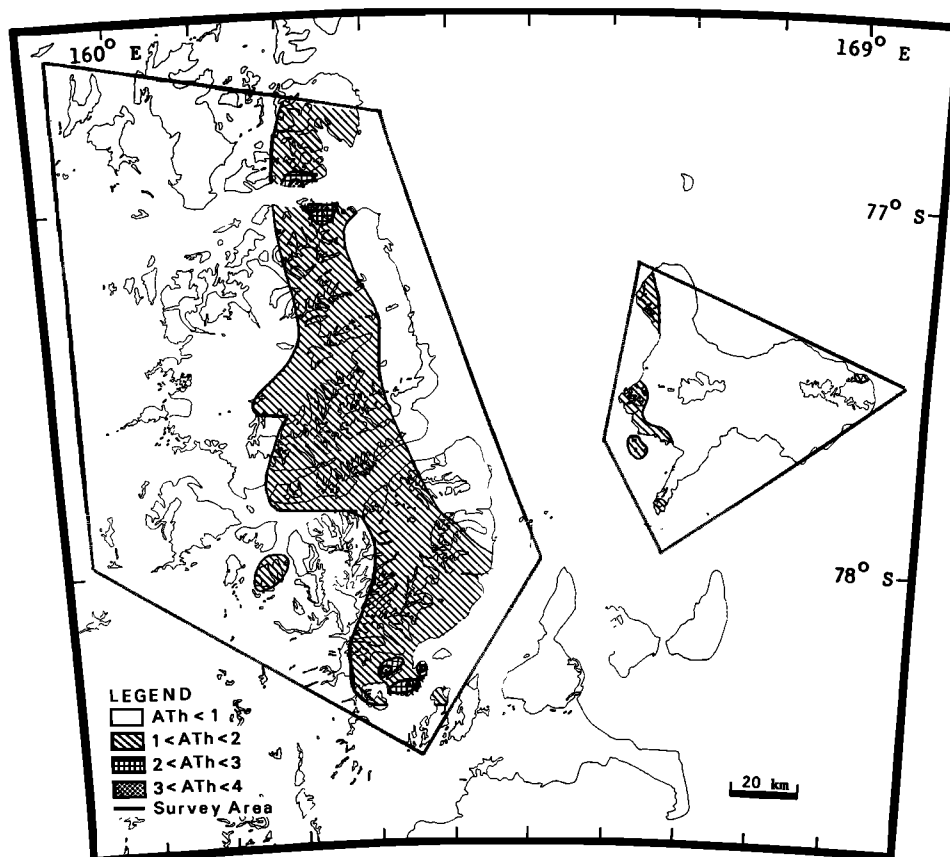


Fig. 8. Map of thorium distribution in the survey area of southern Victoria Land. The thorium has been contoured in dimensionless units using adjusted values based on deviations from the area mean ($ATH = eTh/eTh \text{ survey area}$).

Antarctic rock have been clearly demonstrated in the accumulations of sodium nitrate reported in Antarctic soil [Claridge and Campbell, 1968; Bockheim and Leide, 1980; Bockheim and Wilson, 1981]. Both nitric acid and hydrogen peroxide have been used to leach uranium from ores, and there is no doubt that they would mobilize uranium in outcrop surfaces.

Geological Characteristics and Aerial Extent of the Uranium Mineral Occurrences

The discoveries of uranium mineralization north of the Koettlitz Glacier confirm the existence of uranium-bearing intrusive bodies and define an area of 75 to 100 km² as having uranium resource potential. The area of interest lies between the Koettlitz Glacier and Renegar Glacier on the south and the Radian Glacier and Walcott Glacier on the north. The uranium occurrences in this area have a number of geological characteristics which resemble those of the Rössing uranium mining district of South West Africa [Berning et al., 1976]. The geological age of the deposits in southern Victoria Land is nearly

identical to those at Rössing, and the association of the uranium mineralization with an extensive pegmatite complex is also similar. With reference to the Rössing deposit, Gabelman [1976] states, "However, close inspection of the literature reveals that it may not be a typical pegmatite, which opens an entire new field of consideration of exploration targets." The pegmatites that we examined in the Pyramid Trough are also somewhat atypical of what would be considered normal pegmatites in that they are extremely extensive and do not show the typical sharp boundaries that are commonly seen in most pegmatite occurrences. Furthermore, we have found small quantities of fluorite in some samples from the veins that we discovered. The association of fluorite with uranium deposition is known from a number of other localities, and it is likely that fluorine plays an important role in uranium transport during the primary deposition phase of the pegmatites [Gabelman, 1979].

Preliminary investigations indicate that the principal radioactive mineral is thorite, which occurs as small

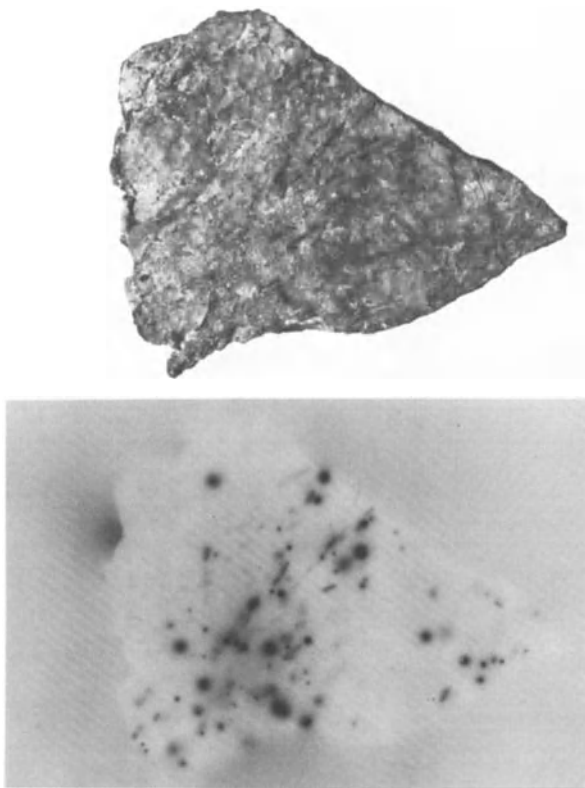


Fig. 9. Photograph and autoradiograph of polished slab from AIRS-2 radioactive mineral site. The slab is 7 cm in length. The dark circular spots in the autoradiograph are caused by the small cubic crystals of uraniferous thorite. The larger, elongated, slightly less darkened zones are caused by crystals of an allanite-like phase. Thin vein fillings are visible near the center of the autoradiograph.

ehedral cubes scattered throughout the rock as shown in Figure 12. These crystals frequently show evidence of their metamict character which is produced by the intense radiation bombardment that results from their high radioelement content. This process causes the crystal lattice to be severely damaged by the radiation and to undergo dilation which produces the starlike cracks in the surrounding rock matrix shown in Figure 13. Many crystals also show evidence of chemical alteration in the form of reddish or greenish yellow alteration rims. The less altered cores of the crystals contain thorium, uranium, and silicon with traces of Pb, Ca, and Y. The alteration rims include these elements together with traces of Fe, Al, La, and rare Earth elements. The thorite is associated with large crystals of an allanite-like phase which is metamict. This phase contains Si, Ca, Ce, light rare Earth elements, Y, Al, and Fe. At AIRS-2 the allanite crystals are totally replaced by what appears to be two carbonate phases.

The most abundant of these is a Ce-rich, Ca, light rare Earth element, Th, U, Fe, carbonate. The other phase appears to contain the same elements but has consistently less Ca and more light rare Earths and La (R. I. Grauch, personal communication, 1987).

Although we do not wish to imply that the highly radioactive veins that we have located have been proven to constitute an economic uranium deposit, there can be no doubt that their large aerial extent requires that they be considered as a highly significant uranium prospect. The similarity of the radiometric signature of the major uranium anomaly at Granite Harbor to that found in the Pyramid Trough area implies that similar types of mineral occurrences might also be expected. Clearly, the Granite Harbor anomaly merits much close reexamination and should be verified by more detailed ground observations.

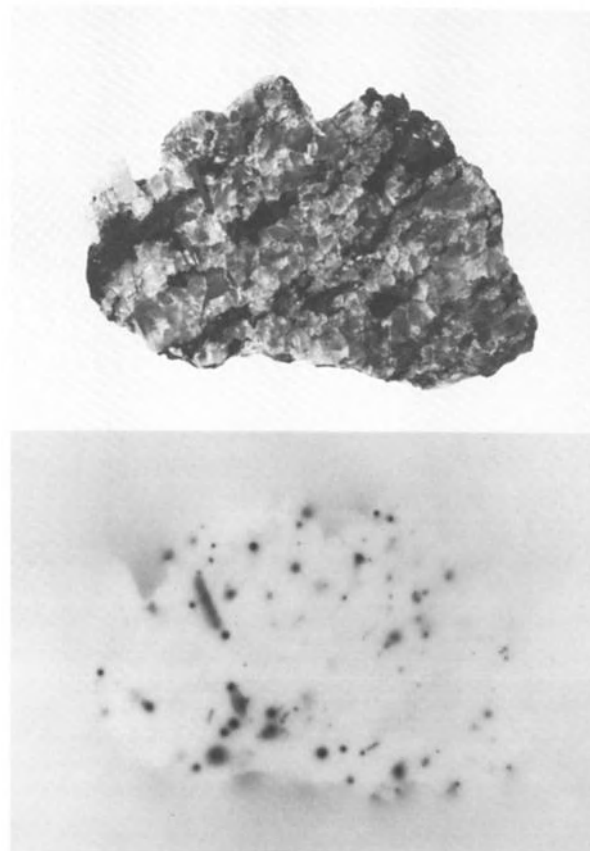


Fig. 10. Photograph and autoradiograph of polished slab from AIRS-3-A radioactive mineral site. The slab is 7 cm in length. The photograph shows the crystalline texture of the pegmatite. The dark mineral is mainly biotite. Dark circular spots in the autoradiograph result from small cubes of uraniferous thorite. The large, elongated crystal visible in the upper left in the photograph and in the same position in the autoradiograph is an allanite-like phase.

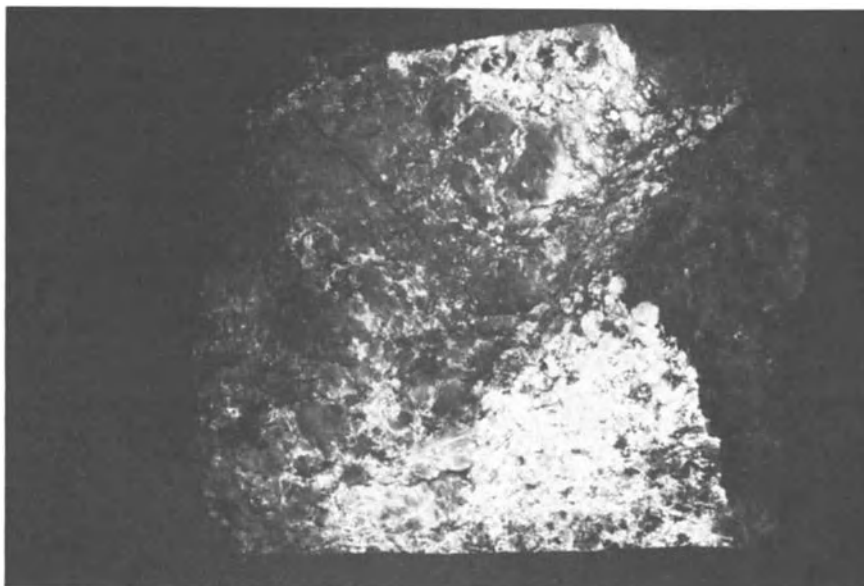


Fig. 11. Photograph of highly fluorescent secondary uranium minerals exposed to ultraviolet light. Secondary uranium mineral coating on fractured surface of rock sample from AIRS-3 site at the head of Pyramid Trough. The strong green fluorescence over most of the surface of the sample indicates the extensive nature of the coating of secondary uranium minerals which are characteristic of this occurrence. The sample is about 20 x 17 cm.

URANIUM ENRICHMENTS AND THE PRE-BEACON EROSION SURFACE

Discovery of Radiation Anomalies Associated With the Pre-Beacon Erosion Surface

In the 1978–1979 field season, radioactive minerals were discovered on the pre-Beacon erosion surface during our radiometric survey activities in the Darwin Glacier and Byrd Glacier areas. It was quickly recognized that the geochemical conditions existing at the time the erosion surface formed were conducive to mobilization and concentration of uranium, and several small radiation anomalies associated with uranium accumulations were detected. In addition, placer-type deposits of thorium-bearing minerals associated with rare Earths and tin were found in conglomerates in the basal Beacon Group sediments at outcrops separated by more than 10 km [Zeller and Dreschhoff, 1980]. The intensity of the radiation anomalies was sufficient to permit easy identification of both types of deposits, and the unconformity became one of the primary targets for all subsequent survey activities. It has been examined at a number of locations throughout the Transantarctic Mountains and has been the source of many of the significant anomalies that were detected by this airborne survey [Zeller and Dreschhoff, 1987].

The unconformity at the base of the Beacon Supergroup was first reported by the geologists of Scott's Western Party in 1905. Debenham [1921] named it the

Kukri erosion surface after exposures near the top of the Kukri Hills between the Taylor Glacier and Ferrar Glacier. The lack of clearly datable fossils in the sediments that lie directly upon the surface make its exact age a matter of conjecture, but most investigators agree that it formed after the Ross Orogeny, between the end of the Cambrian and the beginning of the Devonian. The relief on the surface varies greatly, but it often exceeds 30 m over short distances, and there are rapid facies changes in the sediments resting upon it. The climate and drainage conditions that prevailed at the time of its formation combined to produce intense chemical weathering of the underlying rocks which resulted in leaching and redeposition of uranium in a number of outcrops. A review of the radioactive mineral occurrences on the pre-Beacon erosion surface indicates that there is some similarity between the pre-Beacon surface and some of the erosion surfaces in other parts of Gondwanaland [Zeller and Dreschhoff, 1987].

The Darwin Glacier-Byrd Glacier Area

At Roadend Nunatak on the Darwin Glacier the feldspars in the granite underlying the pre-Beacon erosion surface have been converted to kaolin to a depth of more than 15 m. At this locality the surface is especially well exposed on the southeast spur, and the sedimentary sequence resting directly on it can be examined in detail. The basal contact consists of a few centimeters of

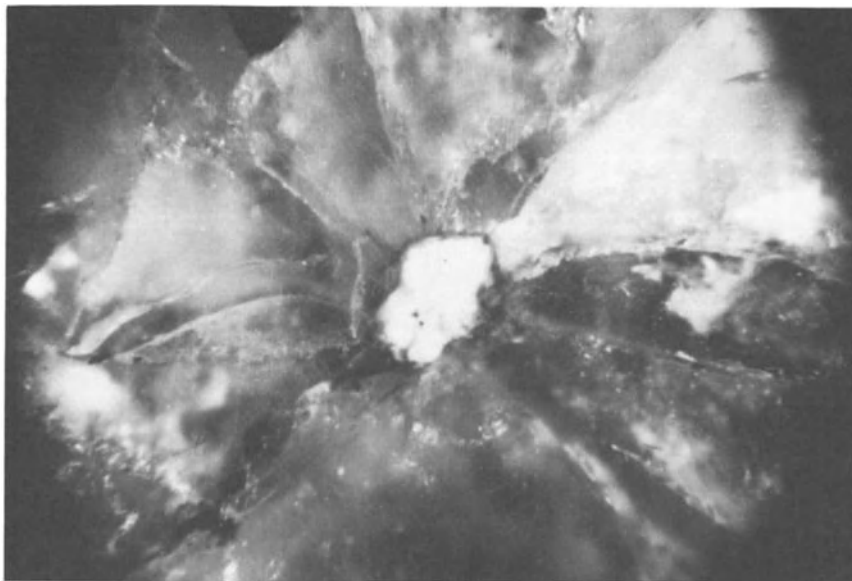


Fig. 12. Typical small cube of thorite showing zonal structure. These cubes are widely disseminated throughout the radioactive pegmatites.

dark clay shale overlain by about 4 m of quartz pebble conglomerate. The entire zone contains radioactive minerals, but the maximum concentration is near the base of the conglomerate where thorium is most abundant. About 5 km east of Roadend Nunatak on the south side of Touchdown Glacier, a sequence of conglomer-

ates and cross-bedded, arkosic sandstones containing thorium, rare Earths, and tin outcrop for more than a kilometer along a ridge. At this locality the actual contact with the underlying granitic rocks cannot be seen, but the conglomerates are similar to those at Roadend Nunatak, and the overlying Beacon Super-

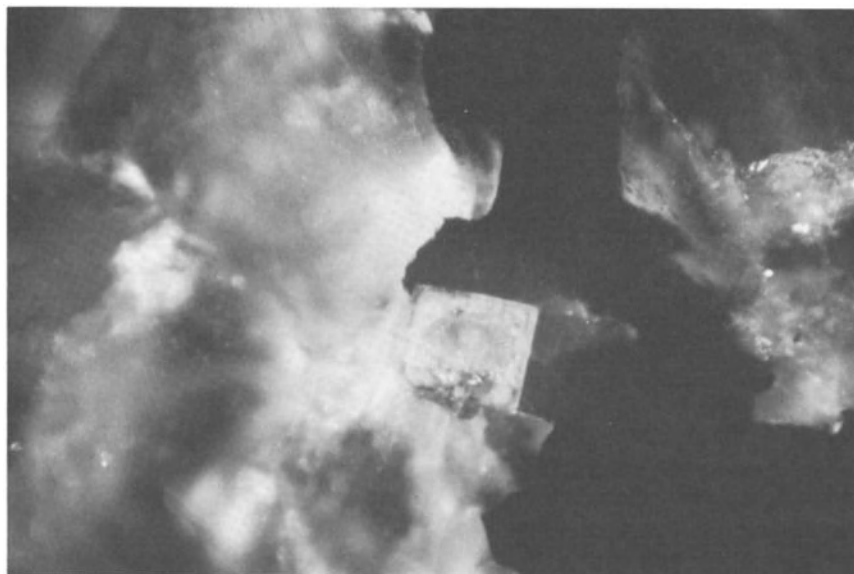


Fig. 13. Star-shaped fracture pattern developed around a metamict crystal. These metamict dilation stars develop when crystals are subjected to heavy radiation damage caused by alpha particles and recoil nuclei from uranium or thorium.

group sandstones are typically developed. At Tentacle Ridge 40 km to the northwest, the unconformity is developed on a mafic igneous complex that also shows evidence of intense weathering.

South of Byrd Glacier, the pre-Beacon erosion surface is developed on a basement consisting of highly contorted metamorphic rocks. At an outcrop located on the divide between the east and west branches of the Zeller Glacier, the flat-lying Beacon Supergroup sediments rest on steeply dipping metasediments of dolomitic marble, phyllite, and conglomerate. At this locality, the basal conglomerate is unusual in that it consists almost entirely of rounded pebbles and cobbles of dolomitic marble which show only slightly elevated radioactivity. However, the thin-bedded quartz sandstones that overlie the coarse carbonate conglomerate show the strongest radiation anomaly associated with uranium that was found south of the Byrd Glacier.

Southern Victoria Land and the Dry Valley Area

The Kukri erosion surface can be examined at a number of localities in southern Victoria Land, and the rocks immediately below it always show some evidence of weathering. The thickness of the weathered zone varies greatly from place to place probably because of the high relief on the surface. Localized radiation anomalies have been detected in weathered material present in fractures in the granite just below the sedimentary contact, and airborne surveys always show anomalous radiation levels associated with the surface throughout the entire area. The surface can be seen in profile along the valley wall of the Ferrar Glacier immediately above the confluence with the icefall at Windy Gully. This outcrop is easily accessible and can be examined in detail on the ground. The underlying rocks show evidence of weathering along the contact, but the oxidized zone is generally only a few centimeters thick on the flank of the granitic hill that forms the eastern portion of the exposure at Windy Gully. Small, localized concentrations of radioactive minerals occur in the thin reddish brown oxidized zone along the contact, but there is little evidence of unusual radioactivity in the coarse basal sandstone which is draped over the hill. At Knobhead and also about 6 km southeast of this outcrop, portions of the Kukri erosion surface have been exposed along the Ferrar Glacier and Emmanuel Glacier. Radiation anomalies associated with both uranium and thorium were detected by airborne surveys over these outcrops. The type exposures of the Kukri erosion surface located along the crest of the Kukri Hills also show increased radioactivity probably related in part to the carbonaceous shales of the Terra Cotta Mountain formation that occur above the contact. The northernmost outcrops of the Kukri surface that we surveyed were on Mount Boreas on the north rim of dry Wright Valley.

These outcrops also show evidence of increased radioactivity, but it is less pronounced than at exposures south of dry Taylor Valley.

Northern Victoria Land

At several places in northern Victoria Land, the pre-Beacon erosion surface has been stripped of sediments and is extensively exposed. Relief is usually low, but an individual remnant hill over 30 m in height was observed at one locality. Although the surface was exhumed by glaciation in the Lichen Hills and Caudal Hills, there is little evidence of modification by glacial erosion over areas of several square kilometers. Portions of the weathered zone that developed when the surface formed have been preserved in pockets of brownish red clay which probably represents the remains of a residual soil that once covered the entire surface. The radioactivity is anomalously high and extremely variable, displaying local enrichments of both uranium and thorium. Most of the uranium enrichments are associated with the old soil zone, but the thorium anomalies were traced to pods of biotite which are common in the megacrystic granite upon which the erosion surface is formed. At Mount Bower in the Outback Nunataks there is a significant uranium anomaly which is clearly located in the basal sandstone beds of the Beacon Supergroup. As in other areas that were surveyed, the pre-Beacon erosion surface of northern Victoria Land shows a number of characteristics which suggest that significant accumulations of radioactive minerals might be present.

CONCLUSIONS

First, the highest potential for uranium resources can be expected in the Transantarctic Mountains associated with the Granite Harbor Intrusives. Among all of the areas that we surveyed, southern Victoria Land appears to have the highest potential. Both primary vein type and secondary uranium minerals are present. The primary deposition of uranium minerals is associated with the extensive pegmatites in southern Victoria Land in the region just north of the Koettlitz Glacier. We found similar large-scale pegmatite terrains in northern Victoria Land where they also display elevated levels of radioactivity. Although these areas are potentially favorable for uranium resources, it is important to note that average concentrations of the highest anomalies are only about half of the values obtained for the highest anomalies in southern Victoria Land. Any sedimentary accumulations of uranium minerals that may be present probably will be associated with the basal Beacon Supergroup rocks resting on the pre-Beacon erosion surface.

In addition to the uranium anomalies that we observed elsewhere, the concentration of thorium and rare

Earths that we discovered on the pre-Beacon surface in the Brown Hills in the Darwin Glacier-Byrd Glacier area is an example of a buried placer, a type of mineral deposit that has been largely overlooked on other continents.

Of the three survey areas in West Antarctica, only Marie Byrd Land shows evidence of anomalous levels of radioelements in the rocks. Although our survey was restricted by the very small number of exposures, we found a generally high radioelement content of some of the granites. They show a trend of increasing radioactivity from east to west across the survey area. There is, however, little evidence for geochemical mobility of the uranium within the survey area, and we failed to find any indication that processes causing a separation of uranium from thorium had been active. Nevertheless, the trend toward increasing radioactivity in the terrains to the west suggests that parts of Marie Byrd Land in the Ford Ranges and Rockefeller Mountains might show a significant uranium resource potential and should be examined at some future time.

The uranium resource potential of the Ellsworth Mountains and the Antarctic Peninsula is difficult to assess on the basis of our limited surveys, but we found little evidence of geochemical concentration mechanisms except for the limited increases in uranium concentrations associated with some of the sulfide deposits in the Antarctic Peninsula.

Finally, any attempt to evaluate uranium resource potential of an area as large and complex as the continent of Antarctica will clearly require a long-range program. The challenge to equipment, logistics, and personnel which the Antarctic environment presents will continue to limit the total effort that can be made to provide a comprehensive uranium resource evaluation. In the foreseeable future, geologists will have to be content with area-by-area reconnaissance assessments of uranium resource potential. The greatest lack in the present survey is the absence of gamma ray data from the old rocks of the Antarctic Shield. These rocks make up a very large portion of the coastal outcrops of East Antarctica, and it should not be difficult to extend the survey by making a series of short flights from an icebreaker.

The data obtained thus far, and any future additions, will add to the sum total of knowledge about the continent and may have valuable spinoff for other kinds of geological studies both in Antarctica and in other parts of the world. If the exploitation of mineral resources ever becomes feasible on the land area of Antarctica, we hope that the data that we have obtained will be useful in delineating targets for the more detailed searches that will be required to define actual ore deposits. At the same time, we also hope that the radiometric data that we have obtained from the continent while it is in an essentially pristine condition will

help to preserve the environment by making it possible to distinguish between naturally occurring radioactive sources and those resulting from human activity.

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GEOHERMAL RESOURCES OF ANTARCTICA

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The potential for geothermal resources in the ice-free areas of Antarctica is evaluated in five categories: conduction-dominated thermal regimes, igneous-related geothermal systems, hydrothermal convection systems, low-temperature geothermal waters, and geopressured-geothermal resources. Antarctica probably lacks major heat flow sources and large hydrothermal convective systems capable of developing conventional geothermal electric power stations. More heat flow measurements are necessary near active volcanoes such as Mount Erebus and along tectonically active areas such as the Transantarctic Mountains to completely exclude the possibility of hot dry rock resources.

INTRODUCTION

With the continuing political uncertainty associated with hydrocarbon supplies and their fluctuations in price, the last two decades have been a period during which increasing efforts have been made to find alternative sources of energy. Among the alternatives, geothermal energy has been widely cited as offering considerable potential for future development. Geothermal electric power schemes throughout the world (particularly Italy, New Zealand, Philippines, and the United States) produce about 1600 MW of electricity [Ellis and Mahon, 1977], equivalent to two average nuclear power plants. Geothermal waters of moderate temperatures (less than 90°C) are used for industrial purposes and for space heating in Iceland, New Zealand, the United States, France, and several other areas. Within Antarctica the only known use of geothermal energy has been at the summit of Mount Erebus, where steaming ground, with temperatures up to 65°C [Lyon and Giggenbach, 1974], has been used to cook meat and to heat scientific instruments. The geothermal activity at Deception Island, which may be related to volcanic eruptions in 1967, 1969, and 1970 [Baker et al., 1969; Orheim, 1972; Shultz, 1972], has attracted the interest of an occasional passing tourist ship.

An assessment of geothermal resources requires an estimation of the amount of extractable thermal energy within the Earth that can be used economically at some reasonable time in the future [Muffler and Guffanti, 1979]. To undertake such an assessment in Antarctica at this time is difficult. Certainly, any assessment must ignore the economic aspects because no prediction can be made of future energy requirements. It is also very difficult to estimate the cost of developing a power

plant, should a suitable geothermal source be discovered.

This paper evaluates the geothermal resources of Antarctica in five categories that are similar to those that Muffler [1979] outlined in an assessment made for the United States. Discussion is limited to the ice-free areas of Antarctica, which is only 5% of the total area of the continent.

HEAT FLOW AND CONDUCTION-DOMINATED THERMAL REGIMES

Regions with elevated heat flow may contain potential geothermal resources, provided some means can be devised to extract the heat. At most locations currently being investigated for geothermal energy, the heat is transported from hydrothermal systems to the surface by water and/or steam. In regions where most of the heat transfer in the crust is by conduction, such convective systems may be considered anomalous.

A number of proposals for methods to recover geothermal energy from "hot dry rock" have been considered [Burnham and Stewart, 1973; Smith et al., 1973; Smith, 1983]. If the technology can be created for an effective method to extract the heat, then large areas of the world could be developed. Present indications suggest that economic factors will be the main obstacle to "hot dry rock" development [Smith et al., 1973; Smith, 1983].

An assessment of conduction-dominated thermal regimes requires a knowledge of regional heat flow. If suitable data are available, then estimates can be made for the amount of heat in the outer 10 km of the crust, if it was cooled to the mean annual surface temperature (see Diment et al. [1975] and Sass and Lachenbruch [1979] for data on the United States).

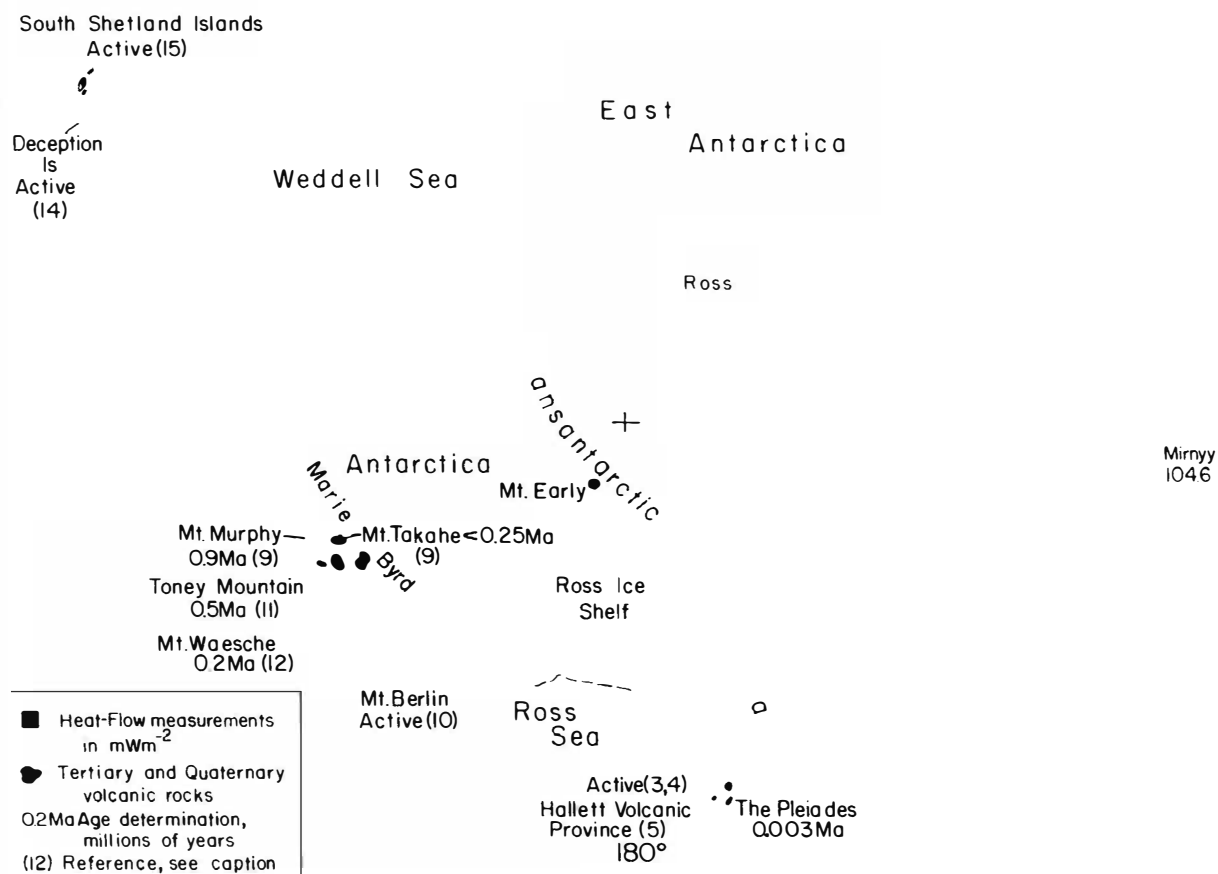


Fig. 1. Location map of Antarctica, showing generalized distribution of Tertiary and Quaternary volcanic rock (after Craddock [1970] and Warren [1969]). Volcanic centers younger than 2 Ma are indicated. Where radiometric age determinations are available, the youngest known age is shown. Insert shows the Erebus volcanic province of the McMurdo Volcanic Group [Kyle, 1990b]. Distribution of exposed rock is indicated by shading. Numbers in parentheses refer to the following references: (1) Sheraton and Cundari [1980], (2) Armstrong [1978], (3) Nathan and Schulte [1967], (4) Lyon and Giggenbach [1974], (5) Hamilton [1972], (6) Kyle et al. [1981], (7) Giggenbach et al. [1973], (8) Treves [1967], (9) LeMasurier and Rex [1982], (10) LeMasurier et al. [1978], (11) LeMasurier [1972], (12) LeMasurier and Wade [1976], (13) Rex [1972], (14) Baker et al. [1969], and (15) Weaver et al. [1979].

In Antarctica, estimates of on-land heat flow have been made only in the McMurdo Sound area and the Mirnyy region (Figure 1). Zotikov [1965] reports a heat flow of 105 mW m^{-2} at Mirnyy. This value was based on an assumed coefficient of thermal conductivity and was apparently uncorrected for local environmental effects. Decker and Bucher [1982] have reported corrected heat flows at Hut Point Peninsula on Ross Island, Lake Vida in Victoria Valley, and at the North Fork of the Wright Valley of 63–67, 79–80, and 100 mW m^{-2} , respectively (Figure 1). Risk and Hochstein [1974] also reported heat flow measurements for Hut Point Peninsula; however, the data of Decker and Bucher [1982] are considered more reliable.

Decker [1978] and Decker and Bucher [1982] suggest

that the McMurdo Sound area is a high heat flow zone that is similar to the Basin and Range high heat flow province in the western United States. Thus the elevation of the Transantarctic Mountains may partly result from temperature anomalies in the underlying mantle. If methods can be developed for the economic recovery of energy from "hot dry rock" geothermal systems, then further geothermal exploration in the Transantarctic Mountains, particularly in the Taylor Valley oasis, may be rewarding.

A number of heat flow measurements have been made in the Ross embayment (Ross Sea/Ross Ice Shelf). Blackman et al. [1987] report two values of 66.3 ± 5.2 and $73.3 \pm 11.7 \text{ mW m}^{-2}$ in the western Ross Sea. These are both significantly higher than the continental

mean of 57 mW m^{-2} . In the central southern Ross Sea, *Sato et al.* [1984] report heat flow measurements between 78.2 and 114 mW m^{-2} , which are twice the continental average. However, there is some question on the reliability of these results [*Blackman et al.*, 1987]. In the eastern Ross Sea, heat flow is reported to be $50\text{--}70 \text{ mW m}^{-2}$ [*Thomas et al.*, 1980], and beneath the Ross Ice Shelf a value of 54.4 mW m^{-2} [*Foster*, 1978] has been determined. These show that no abnormal thermal conditions occur in the area.

IGNEOUS-RELATED GEOTHERMAL SYSTEMS

An estimate of thermal energy in igneous-related geothermal systems is based on evidence for the existence of high-level silicic magma chambers, their volume, and the age of their latest eruptions [*Smith and Shaw*, 1979]. To generate recoverable heat, the magma chamber must be in the upper 10 km of the crust. For a 5-km-thick magma chamber, estimates suggest it would take about 2 m.y. for the chamber to cool from $\sim 850^\circ\text{C}$ to ambient temperature [*Smith and Shaw*, 1979].

Extensive Tertiary and Quaternary volcanism in Antarctica is well documented in three main geographic localities (Figure 1): the western Ross Sea, Marie Byrd Land, and the Antarctic Peninsula. Isolated volcanic vents are found at Gaussberg and Mount Early. Almost all of the volcanic rocks are alkalic (some strongly alkalic) or subalkalic, except for the strongly potassic lavas at Gaussberg. Although basaltic rocks are predominant in all areas, differentiates do occur in some volume, particularly in Marie Byrd Land.

Large silicic calc-alkaline intrusive bodies are the favored source for igneous-related geothermal systems. No such young (<5 Ma) bodies are currently known in Antarctica. However, cooling magma chambers of phonolitic, trachytic, and silicic peralkaline compositions probably occur in areas and may be large enough to be considered as potential geothermal resources.

The distribution of Late Cenozoic volcanic rocks and major volcanic vents younger than 2 Ma is indicated in Figure 1. Individual areas are discussed below.

Gaussberg

Fission track ages of 25 ± 12 ka on the leucitite from Gaussberg suggest that this vent is several orders of magnitude younger than was previously indicated by K-Ar ages of 20 and 9 Ma [*Sheraton and Cundari*, 1980]. The basic, K_2O -rich lavas are not of the type that form large high-level magma chambers; therefore the area may not have any significant potential as a geothermal resource.

Hallett Volcanic Province

The volcanic rocks of the Hallett volcanic province are of late Miocene, Pliocene, and Quaternary age.

From a limited number of K-Ar dates, the youngest is 1.14 Ma old [*Hamilton*, 1972; *Kruezer et al.*, 1981]. *Hamilton* [1972] suggested that the four major volcanic piles which make up the province should be considered active (*sensu lato*). Alkali basalt and hawaiite are dominant, but more evolved felsic rocks such as trachyte and phonolite are common. Most of the known felsic rocks occur as small, isolated outcrops that are not suggestive of eruption from large high-level magma chambers. At present, the Hallett volcanic province must be considered to have very little geothermal potential.

Melbourne Volcanic Province

Two young felsic eruptive centers, Mount Melbourne and The Pleiades, occur in the Melbourne volcanic province [*Kyle*, 1990a].

Mount Melbourne is active [*Nathan and Schulte*, 1967] with geothermal activity consisting mainly of steaming ground. *Lyon and Giggenschbach* [1974] reported temperatures as high as 59°C , at depths of about 0.25 m beneath the ground surface. Although *Nathan and Schulte* [1967] reported hearing boiling or running water here, their observations were not confirmed by *Lyon and Giggenschbach* [1974]. Hydrothermal sinter at Mount Melbourne indicates that hot aqueous thermal fluids have been present in the past [*Lyon and Giggenschbach*, 1974].

Some of the geothermal activity at Mount Melbourne is associated with small young craters surrounding a 1-km-diameter summit caldera [*Worner and Viereck*, 1989]. Much of the present activity is probably derived from residual heat which resulted from recent eruptions of trachyte and trachyandesite lavas. The small size of young parasitic cones and plugs and the confinement of geothermal activity to the summit area of Mount Melbourne all suggest that the volcano does not contain a large (>5 km in diameter) high-level (<10 -km depth) magma chamber.

K-Ar dates of four samples from The Pleiades range from 3.0 ± 14.0 ka to 40.0 ± 50.0 ka [*Armstrong*, 1978; *Kyle*, 1982]. The lavas are mainly felsic, varying from trachyandesite to peralkaline trachyte. The youngest eruptives are more undersaturated and sodic, consisting of Ne-hawaiite to Ne-benmoreite compositions [*Kyle*, 1982], and their field relationships suggest that they were erupted from a single compositionally zoned magma chamber. There is no caldera or geothermal activity here; hence a large high-level magma chamber is not suggested. Perhaps cooling intrusive bodies underlie The Pleiades, but available data imply that they are likely to be too small and too deep to constitute a potential geothermal resource.

Erebus Volcanic Province

Many eruptive centers younger than 2 Ma occur in the Erebus volcanic province (Figure 1, insert) [Kyle and Cole, 1974; Armstrong, 1978; Kyle, 1990b]. The great majority of these centers are basaltic or are associated with small phonolitic plugs and cones. Mount Erebus may offer some potential as a geothermal resource area. However, before discussing the Mount Erebus area, it is pertinent to examine the results of the Dry Valley Drilling Project (DVDP), a program that drilled three holes (DVDP 1, 2, and 3; see Figure 1) in the young volcanic rocks of Hut Point Peninsula. Moreover, the nature of the volcanism at Hut Point Peninsula is typical of many areas in the Erebus volcanic province, such as Cape Crozier and Mount Morning.

Hut Point Peninsula consists of small basaltic scoria cones and lava flows that erupted from 0.43 Ma to perhaps >1.6 Ma ago [Kyle, 1981a]. Observation Hill, a small phonolite cone, is 1.2 Ma and overlies the DVDP 2 and 3 drill sites. DVDP 2 and 3 drill cores reveal a thick hyaloclastite pedestal overlain by basanite lava flows and pyroclastic rocks and then intermediate differentiates of Ne-hawaiite, Ne-mugearite, and Ne-benmoreite compositions [Kyle, 1981b]. Geochemical and mineralogical studies suggest that a high-level (<10 km) magma chamber underwent differentiation and gave rise to most of the intermediate rocks and the phonolite at Observation Hill [Kyle, 1981b]. K-Ar ages indicate that this occurred about 1.3 Ma [Kyle et al., 1979]. A corrected heat flow value of 63–67 mW m⁻² for the 381-m-deep DVDP 3 hole is one of the lowest measured in the McMurdo Sound area. Permafrost may extend to more than 500 m beneath ground surface at Hut Point Peninsula [Decker and Bucher, 1982]. Although volcanism has occurred in the last 0.5 Ma and a high-level magma chamber was probably present at 1.3 Ma, there is no evidence of residual heat from magmatism near Observation Hill at present.

Mount Erebus is currently active and contains a persistent convecting magma lake [Giggenbach et al., 1973; Kyle et al., 1982]. Preliminary models suggest that the magma in the lake originates in an underlying large magma chamber. Activity at Mount Erebus has persisted since 1 Ma and has resulted in eruptions of anorthoclase phonolite lavas which are very similar to those presently in the magma lake [Kyle, 1977]. This constancy of composition could be interpreted to indicate the presence of a large permanent magma chamber in the upper 10 km of crust. The magma lake at Mount Erebus has shown no compositional change or crystallization since 1972 (P. R. Kyle, unpublished data, 1988), and there is no apparent cooling. Convection is responsible for the continued existence of the magma lake; however, as the heat loss must be considerable (no estimates have yet been made), this implies that the

connecting magma chamber must also be of considerable volume.

It must be concluded that Mount Erebus may be a viable geothermal resource area and that research to determine the size, shape, and depth of the present magma chamber will have both economic and academic significance. Deep drilling in the area between Cape Evans and Cape Royds may help to understanding the thermal regime of the Mount Erebus area and the potential for geothermal development. If a magma chamber can be located at shallow levels, a "hot dry rock" resource area could be implied because a major hydrothermal system is unlikely (see discussion below). Therefore any exploitation must await the development of appropriate technology to harness such geothermal energy in Antarctica. The main advantage of the Cape Evans-Cape Royds area is its close location to McMurdo Station and access to the sea that would provide easy transfer of equipment and materials necessary for plant development.

Marie Byrd Land Volcanic Province

Five volcanoes in this province that have been active in the last 2 Ma are identified in Figure 1. Being isolated and extensively covered with ice, these volcanoes are unlikely to have any significant economic value as geothermal resources. Only preliminary reconnaissance geologic mapping of the volcanoes has been conducted [LeMasurier, 1972; Gonzalez-Ferran and Gonzalez-Bonorino, 1972; LeMasurier and Wade, 1976]. Mount Berlin may be active [LeMasurier et al., 1978], but the latest eruptive history is not accurately known. Mount Takahe has apparently erupted frequently during the period from 15 to 45 ka [Palais et al., 1988]. A large number of peralkaline trachyte tephra layers in an ice core from the West Antarctic ice sheet have been tentatively correlated with Mount Takahe eruptions [Kyle and Jezek, 1978; Kyle et al., 1981; Palais et al., 1988]. Because of the frequent eruptions, the occurrence of an 8-km-diameter summit caldera, and the chemical compositions of the tephra, it is possible that a large silicic peralkaline magma chamber is present below Mount Takahe.

Other volcanoes in the Marie Byrd Land volcanic province are so poorly known that even preliminary suggestions as to their suitability as sources of geothermal energy are not attempted herein.

Antarctic Peninsula

Quaternary volcanism occurred on the South Shetland Islands, James Ross Island and vicinity, and Seal Nunataks (Figure 1). Although much of the youngest activity is basaltic, slightly evolved hawaiites are also common, especially on James Ross Island [Baker, 1976; Baker et al., 1976; Weaver et al., 1979].

Eruptions on Deception Island occurred in 1967, 1969 [Baker *et al.*, 1969], and 1970, and a large caldera with a diameter of ≤ 10 km occurs here. Some postcaldera collapse rocks are dacitic in composition. Volcanism is probably in its waning stages, but further eruptions are likely [Shultz, 1976]. The small extent of the dacitic rocks [Hawkes, 1961; Baker *et al.*, 1975] is not suggestive of a large (>5 km) magma chamber in the upper crust. Probably damage by future eruptions would also curtail development of local geothermal resources.

HYDROTHERMAL CONVECTION SYSTEMS

Hydrothermal convection systems with temperatures greater than 90°C are one of the main sources of present-day geothermal energy. These systems are subdivided into hot water and vapor-dominated systems, respectively, depending on whether liquid water or steam is the continuous press-controlling phase in the reservoir [Brook *et al.*, 1979].

In hydrothermal systems the hot water and/or resulting steam is meteoric water that has been cycled to depth, is heated there, and then rises to the surface for temporary storage in a reservoir. Convection is important in these systems [Ellis and Mahon, 1977].

Antarctica is a desert, with very minor precipitation. In areas of bare ground, permafrost is ubiquitous. Thus there is little or no meteoric water in the region, and an impermeable permafrost barrier probably precludes downward water flow and subsequent heating. Also, during winter, small ephemeral streams found in some areas of Antarctica freeze up and halt any recharge to groundwater systems. By these views, many parts of Antarctica are unlikely to contain in-board, nonsaline hydrothermal systems.

Hydrothermal systems resulting from heating of seawater are known to occur in Hawaii and Iceland. These could occur in some near-sea areas in Antarctica, such as about Ross Island.

LOW-TEMPERATURE GEOTHERMAL WATERS

Thermal springs and other low-temperature ($<90^{\circ}\text{C}$) geothermal waters are common throughout the world and are often used for cooking, bathing, healing, etc. Such waters also have been used for space heating and in agriculture [Sammel, 1979].

As discussed above, precipitation in Antarctica is low, and permafrost probably restricts the development of significant groundwater or hydrothermal systems. Thus there appears to be little likelihood of finding low-temperature geothermal waters which can be of economic value, except perhaps on Deception Island, where heated seawater from shallow hydrothermal reservoir is present and frequently attracts the attention of bathers from tourist ships.

GEOPRESSURED-GEOTHERMAL RESOURCES

Sedimentary rocks with pore fluids under higher than normal confining pressure are termed "geopressed," and the energy contained in them is termed "geopressed-geothermal energy" [Wallace *et al.*, 1979]. Water in such sediments can be hot, may be saturated with dissolved methane, and may offer a potential source of energy. Evaluation of geopressed-geothermal resources in the United States is still in its infancy [Wallace *et al.*, 1979]. The technology necessary to economically recover geopressed-geothermal energy has yet to be developed.

In Antarctica, no suitable Tertiary or Mesozoic sedimentary basins occur in ice-free areas on land. The Ross Sea, Weddell Sea, and other areas around the continental shelf contain considerable thicknesses of sediments, which may be suitable for exploration. Present-day costs of marine drilling and the associated problems of ice movement negate any near-future development in Antarctica. If future oil exploration does occur on the continental shelf of Antarctica, then data may be forthcoming and an assessment of the geopressed-geothermal energy resources may be attempted.

CONCLUSIONS

A quantitative assessment of geothermal resources of Antarctica cannot be made at this time because of the paucity of heat flow and other thermal data [cf. Muffler, 1979]. However, qualitative evaluations of known geologic and hydrologic environments suggest that Antarctica probably lacks numerous major high-heat sources and large hydrothermal convection systems. Considered together, aridity and presence of a permafrost cap probably exclude development of conventional geothermal electric power stations that are similar to those in operation at The Geysers in the United States and at Wairakei in New Zealand. However, seawater hydrothermal systems may be found below small island and shoreline volcanoes, and one such area may be Deception Island.

Extensive research is currently being carried out mainly in the United States to develop technology to extract thermal energy from hot dry rocks. Hot dry rock resources probably occur in (1) conduction-dominated regimes and (2) igneous-related systems. Both regimes cannot be completely discounted in Antarctica. More heat flow measurements along the Transantarctic Mountains and continued study of the magma chamber at Mount Erebus may offer insight into future potential for hot dry rock systems in these areas. Additionally, deep bedrock drilling will be necessary, and such extremely expensive ventures may require an international cooperative program to share the cost. Strategically placed drill sites could yield a valuable scientific return as well as provide data for a reliable, detailed assessment of regional geothermal resources.

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BANDED IRON FORMATIONS IN EAST ANTARCTICA

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Banded iron formations are common in the basement shield areas of several continents, and it is not surprising that they should be present in Antarctica. They have been recognized at a number of localities extending around the coast from Enderby Land to Wilkes Land in East Antarctica. The Mount Ruker exposures in the southern Prince Charles Mountains are regarded by some investigators as large enough to be classified as a potential ore deposit. However, exploitation of this resource is unlikely for a number of reasons. The iron content averages 33.5%, and ore of this grade would normally require beneficiation, most probably at the mine site. The high cost of mining and the expense of ocean transport from Antarctica to a steel mill would further inhibit exploitation. In addition, the phosphorus content of the ores is marginal for modern steel-making methods. All of these factors combine to make it unlikely that commercial development of these resources will be possible in the foreseeable future.

INTRODUCTION AND PREVIOUS INVESTIGATIONS

Banded iron formations in East Antarctica have received (and will probably continue to receive) significant attention in assessments of the mineral resource potential of Antarctica [Wright and Williams, 1974; Lovering and Prescott, 1979; Behrendt, 1983], and emphasis has been given to the rocks exposed at Mount Ruker in the southern Prince Charles Mountains. Some authors consider the Mount Ruker banded iron formation exposures large enough to warrant classification as a potential ore deposit (as distinct from a mineral occurrence) [Holdgate and Tinker, 1979], but economic exploitation is unlikely for many years given Mount Ruker's remote location and the difficult access to it.

The first report of iron-rich rocks from East Antarctica was probably that of Kleeman [1940] (see also Mawson [1940a, b]), who described a hematite-magnetite jaspilite (specimen 360) from the moraines at Cape Denison, Adélie Coast; Mawson [1940a] also reported magnetite schist and magnetite-bearing schist from this locality. The first reported outcrop of iron-rich rocks was of a lenticular body of magnetite-rich rock within "highly altered metasediment" described from Edward VIII Bay, Kemp Coast, and the Amundsen Bay area of Enderby Land by Crohn [1959].

In 1956, geologists of the Soviet Antarctic Expedition found fragments and large (1.5–2.0 m) subrounded boulders of hematite-bearing ferruginous quartzite (jaspilite) in moraines in the Vestfold Hills area [Ravich and Voronov, 1958; Ravich, 1960]. Ravich *et al.* [1965] noted that the source of these jaspilites was unknown but

speculated on the possibility of an iron ore basin in East Antarctica "similar to the large Lower Proterozoic iron ore deposits known elsewhere in the world" [Ravich *et al.*, 1965, p. 452]; they also commented that magnetite schist and gneiss had been found, mainly in slightly migmatized gneisses, in the Bunger Hills, Enderby Land, Queen Maud Land, and elsewhere, and they observed that in Enderby Land magnetite mineralization is in brecciated zones 10–50 m thick and at least 100 m long. They postulated a metasomatic origin for the Enderby Land magnetite-rich zones and noted that the "iron ore" occurrences in Queen Maud Land appear to be spatially related to the widespread charnockite massifs.

The Soviet discoveries in the Vestfold Hills were followed in 1960 by Australian geological exploration in the southern Prince Charles Mountains and Ruker's [1963] report [Trail, 1963, 1964] of very well rounded boulders, several feet in diameter, of hematite, and smaller fragments of jaspilite in the moraines along the north side of Mount McCauley and Mount Scherger. Ruker [1963] felt unable to speculate on the provenance of these erratics but noted that hematite was 9 times more abundant than magnetite in the rocks.

Soviet geologists followed the Australians into the southern Prince Charles Mountains in 1965–1966, and Soloviev *et al.* [1967] described a 200-m-thick outcrop of jaspilite on the northern slope of Mount Ruker, on the southern flank of Fisher Glacier, more or less directly opposite Mount McCauley and Mount Scherger. No emphasis was placed on the discovery, but the expedition leader, Maksutov [1967], refers to "very interesting

material'' and ''a large iron ore formation of the ferruginous quartzite type . . . discovered for the first time in this region of Antarctica.''

The same Mount Ruker outcrop was described by Soloviev [1972], who estimated that some 70 m of jaspilites were exposed there. Further Soviet work in the same general area in 1972 is described by *Grikurov and Soloviev* [1974], who refer to moderately and steeply dipping, intricately and isoclinally folded jaspilite units exposed in a 500- to 600-m-wide zone. They do not describe the constituent mineral assemblage of the jaspilites. *Halpern and Grikurov* [1975] give an alternative interpretation of the geology of the Mount Ruker area and suggest that the calcareous schists and sandstones at nearby Mount Rubin are younger than the Mount Ruker rocks because they are not intersected by mafic intrusions like those observed in the Mount Ruker sequence and because they include conglomerates which contain jaspilite clasts.

Soviet geological work in the southern Prince Charles Mountains continued in 1973, and although no further geological studies were conducted at Mount Ruker, widespread aeromagnetic surveys were carried out. The results are described by *Fedorov et al.* [1982] and are featured in a review of the Prince Charles Mountains ''iron ore'' deposits by *Ravich et al.* [1982]. These authors describe the Mount Ruker ''jaspilites'' as containing magnetite and hematite in the ratio of 3:2 and give a number of chemical analyses.

Australian geologists first visited the Mount Ruker ''jaspilite'' outcrop in 1973 and returned the following year to make more detailed studies [*England and Langworthy*, 1975]. They observed that the predominantly dark blue colored jaspilites contain about 20% magnetite and virtually no hematite. Consequently, they will be described as banded iron formations in the remainder of this paper. Soviet and Australian geological studies in the Prince Charles Mountains have shown that banded iron formations are exposed only at Mount Ruker, although erratics are widespread. Similar rocks are reported [*Pieters and Wyborn*, 1977; *Sheraton et al.*, 1980] from Enderby Land, where the largest occurrence (at Newman Nunataks), though perhaps more accessible, is much smaller than the Mount Ruker outcrop.

BANDED IRON FORMATION LOCALITIES

Mount Ruker, Southern Prince Charles Mountains

Mount Ruker is on the southern flank of Fisher Glacier, the major tributary of Lambert Glacier, which is the world's largest glacier and which drains into the Amery Ice Shelf. *Wellman* [1982] postulates that Fisher Glacier has a propensity to surge, and he cites as part of his evidence a prominent moraine near the west end of Mount Ruker [*England and Langworthy*, 1975, Plate 3].

Allison [1979] concludes that bottom melting is widespread in the Lambert Glacier system including Fisher Glacier, a factor that will enhance glacier velocity. Mount Ruker's situation on the inland side of Fisher Glacier constitutes a major obstacle to possible economic exploitation. In addition, Mount Ruker is located 650 km from the Mac. Robertson Land coast, which is only accessible for about 6 weeks of the year.

The Mount Ruker banded iron formation occurs within a metasedimentary sequence that unconformably overlies a granitemass at the east end of the mountain [*England and Langworthy*, 1975; *Tingey*, 1982a, b; *Tingey et al.*, 1981]. *Halpern and Grikurov* [1975] suggest that the granite is between 2000 and 3000 m.y. old, while unpublished Rb-Sr data of P. A. Arriens (personal communication, 1975) define a metamorphic age of about 1400 m.y. *Tingey* [1982b] assigns the Mount Ruker basement granite to the Archean basement of the southern Prince Charles Mountains on the basis of arguments presented by *Tingey* [1982a]. The metasedimentary sequence is of unknown age, but it is thought to be older than about 1400 m.y., and possibly as old as 2600 m.y. [*Tingey*, 1982a].

Although the prominent banded iron formation outcrop, first described from the northern cliffs of the mountain by Soviet workers [*Soloviev et al.*, 1967; *Soloviev*, 1972; *Grikurov and Soloviev*, 1974], is clearly the largest and most important, other banded iron formation lenses are mapped out by *England and Langworthy* [1975] and by *Tingey* [1982b]. The enclosing metasedimentary sequence is described [*England and Langworthy*, 1975] as consisting of white and limonite-stained orange quartzites, greenish quartzites with the chromium mica fuchsite, chlorite-white mica-quartz schists, chloritic phyllites, dolomite-rich chlorite schists, black chlorite-carbonate-actinolite-biotite slates, banded iron formations, metamorphosed basic and fine-grained porphyritic andesitic volcanic rocks, and minor talc-carbonate rocks; a complete gradation between black slate and banded iron formation is also noted. The nature of this sedimentary sequence, with a relative dearth of volcanic rocks, prompts classification of the banded iron formation as a Lake Superior type [*Gross*, 1970], although some features of this type are absent, perhaps because of metamorphic effects.

England and Langworthy [1975] describe the metasedimentary sequence as being of low metamorphic grade. Typical banded iron formation consists of about 20% magnetite, 60% quartz, 15% carbonate with accessory dark brown biotite or stilpnomelane, and very fine-grained garnet in certain manganese-rich varieties. The alkali amphibole, riebeckite, is also a common constituent and is compatible with the low metamorphic grade indicated by the presence of actinolite, chlorite, carbonate, and stilpnomelane. In contrast, *Ravich et al.* [1982] describe the banded iron formations as consisting

of magnetite and hematite in a 3:2 ratio, with granoblastic quartz, and various amounts of carbonate, alkali amphibole (riebeckite), albite and microcline, brown biotite, and green mica. They postulate that alkali metasomatism has produced the riebeckite, albite, microcline, and green mica and cite as supporting evidence the relative concentration of these minerals along the boundaries between opaque-rich and quartz-rich layers in finely laminated banded iron formations. This distribution is readily explicable as a function of the original composition of the heterogeneous rock, but the varied CaO contents of the analyzed Mount Ruker banded iron formations might be interpretable as evidence of metasomatic activity. In any case, there is no suggestion that the metasomatism resulted in any redistribution of the iron in the rocks.

England and Langworthy [1975] evidently do not believe that the Mount Ruker metasedimentary sequence is intruded by mafic igneous rocks, a view that contrasts with that of Soloviev [1972] and with the detailed account of Ravich *et al.* [1982], who describe some metabasite-banded iron formation contacts as "certainly intrusive." Tinge *et al.* [1981] examined the whole of Mount Ruker and concluded (as did Tinge [1982a]) that metabasites do intrude the metasedimentary sequence.

Doubts about stratigraphic relationships at Mount Ruker are functions of limited bedrock exposure, the ruggedness of the terrain (Mount Ruker's northern cliffs are 300 m high and very steep), and the comparatively limited amount of fieldwork completed at Mount Ruker to date. Uncertainties also apply to estimates of the banded iron formation thicknesses at Mount Ruker: for example, Ravich *et al.* [1982] detail a 380-m-thick section from a bedrock outcrop 1000 m long and about 150 m high at the eastern end of cliffs on the north face of Mount Ruker, and apparently including the 70 m section described by Soloviev [1972]. England and Langworthy [1975] estimate a "visible" thickness of some 750 m of banded iron formation and a somewhat smaller true thickness in the same area.

Structure

Ravich *et al.* [1982] state that a reliable stratigraphic sequence cannot be deduced for the Mount Ruker metasedimentary sequence because the rocks are "highly tectonically disturbed." However, although England and Langworthy [1975], in their account of the geological structure of the main banded iron formation locality, note that complex patterns of open concentric and highly flattened mesoscopic folds are ubiquitous, they conclude that the dominant fold mechanism was a simple buckling in response to a single deformation. Multiple competent siliceous layers were buckled by this deformation which produced complex flow folds in incompetent interlaminated ferruginous rocks. Large-

scale recumbent style folding has been noted in several parts of the southern Prince Charles Mountains including Mount Rubin, immediately to the east of Mount Ruker, and is attributed by Tinge [1982a, b] to late Proterozoic tectonism. It is likely that the apparent complexity of folding in the Mount Ruker banded iron formations (and in similarly incompetent calcareous shales on Mount Rubin) is largely a function of lithological competence, but recumbent and isoclinal fold styles are known from nearby outcrops [Tinge and England, 1973; Tinge, 1982a] and are probably present in the Mount Ruker sequence.

Economic Potential

Chemical analyses of random, but probably reasonably representative, samples of the Mount Ruker banded iron formations are shown in Table 1 (analyses 1–27); total Fe contents range from 24.1% to 45.9% and average 33.5%. Economic exploitation of ore of this grade would normally involve beneficiation, a process almost invariably carried out at the mine site. Furthermore, the phosphorus content of the Mount Ruker banded iron formations appears to be marginal for modern steel-making methods, which require ores with either less than 0.08% or more than 2.0% P [Mead, 1974]. This is equivalent to P_2O_5 contents of 0.18% and 4.6%, respectively ($0.0436\% P_2O_5 = \%P$). Given the remote locality and difficulties of access to Mount Ruker, it is evident that the economic potential of the banded iron formations there is very small.

Ore deposits with iron contents comparable to those of the Mount Ruker rocks are mined in several parts of the Soviet Union [United Nations, 1970, Table 2, pp. 392–419] and in the Lake Superior area of the United States [United Nations, 1970, Table 3, pp. 455–467]. They are connected to heavy industrial centers by convenient and relatively cheap surface transport. In contrast, the Mount Ruker banded iron formations are remote and accessible with difficulty from an ice-bound coastline that is only accessible to conventional shipping for at most 6 weeks each year. This coast is itself some 5000 km from the nearest populated landmass: Australia, a major iron ore exporter now and for many years to come, with economic iron ore resources estimated at 21,600 million tons in 1980 [Bureau of Mineral Resources, Geology and Geophysics, 1980]. It is perhaps appropriate to note that reserves of 14,500 million tons of iron ore with more than 55% Fe are quoted by the United Nations [1970] just for Western Australia's Hamersley Basin, where no effort has yet been made to assess reserves of beneficiable ore containing less than 50% Fe [United Nations, 1970, p. 209]. Australian estimates of the iron ore reserves in the Hamersley Basin tend to be somewhat higher than those quoted by the United Nations [1970], with Mead [1974], for exam-

TABLE 1. Banded Iron Formations (in Percent) From Mount Ruker and the Vestfold Hills

	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	51.46	53.12	60.58	49.54	42.15	60.32	40.70	48.68	49.58	57.30	35.84	42.34
TiO ₂			tr	0.01					tr	tr	0.04	0.07
Al ₂ O ₃	1.18	0.54	0.32	1.60	0.65	0.61	0.37	0.53	0.67	1.15	1.35	0.66
Fe ₂ O ₃	33.38	34.05	26.72	27.18	40.06	25.59	38.48	31.70	34.04	26.03	40.96	39.81
FeO	8.80	8.15	7.00	13.34	12.35	8.58	14.04	11.35	10.48	10.97	16.39	9.88
MnO	0.13	0.12	tr	0.17	tr	tr	0.31	tr	tr	0.16	0.16	0.09
MgO	1.30	1.32	1.58	1.55	1.96	2.07	1.76	2.29	1.51	1.50	2.23	1.71
CaO	0.78	0.48	1.26	1.94	0.56	0.75	1.29	0.68	0.76	0.80	0.56	1.52
Na ₂ O	0.16	0.83	0.07	0.19	1.24	1.40	0.64	2.78	0.89	0.60	0.65	0.90
K ₂ O	0.11	0.11	0.04	0.84	0.15	0.25	0.25	0.55	0.42	0.18	0.58	0.75
P ₂ O ₅	0.08	0.11	0.10	0.62	0.08	0.08	0.11	0.44	0.08	0.08	0.06	0.48
Ignition loss	2.20	0.75	2.34	3.21	0.78	0.64	2.33	0.76	1.43	1.54	1.29	1.68
H ₂ O	0.16	0.20	0.30	0.12	0.12	0.24	0.04	0.20	0.14	tr	0.14	0.10
Total	99.58	99.58	100.01	100.17	99.98	100.29	100.28	99.76	100.06	100.31	100.11	99.89
% Fe (total)	30.1	30.1	24.1	29.4	37.6	24.6	37.8	31.0	32.1	26.7	41.3	35.5
	13	14	15	16	17	18	19	20	21	22	23	24
SiO ₂	43.64	43.87	47.31	53.99	41.68	46.08	42.92	44.70	36.93	53.2	61.4	29.8
TiO ₂	0.03	0.07	0.03	tr	0.05	0.07	0.03	0.10	0.03	0.01	0.01	0.00
Al ₂ O ₃	0.36	0.36	0.54	0.24	0.43	0.38	0.35	1.22	0.46	0.91	0.30	0.28
Fe ₂ O ₃	34.85	39.78	29.01	27.56	39.81	36.90	35.08	29.98	45.77	42.9*	36.1*	65.6*
FeO	14.77	10.52	14.65	11.33	13.59	12.33	14.48	14.66	11.31			
MnO	0.11	0.12	0.25	0.15	0.09	0.18	0.28	0.35	0.11	0.06	0.22	0.09
MgO	1.57	1.10	1.69	1.62	1.32	1.54	1.44	2.04	1.70	1.52	0.91	2.08
CaO	1.29	0.96	1.07	1.18	0.59	0.73	1.34	1.55	1.30	1.44	0.88	0.26
Na ₂ O	0.52	0.42	0.31	0.72	0.48	0.70	0.34	0.21	0.60	n.d.	n.d.	n.d.
K ₂ O	0.32	0.25	0.54	0.34	0.50	0.30	0.47	0.95	0.45	0.27	0.31	0.36
P ₂ O ₅	0.13	0.14	0.26	0.17	0.12	0.14	0.32	0.19	0.17	0.16	0.24	0.00
Ignition loss	2.50	2.10	4.43	2.38	1.19	0.91	2.68	3.83	1.20	0.61	0.24	0.00
H ₂ O	0.14	0.14	0.12	0.22	0.24	0.23	0.15	0.16	0.16			
Total	100.09	99.69	100.09	99.68	99.85	100.26	99.73	99.78	100.03	101.08	100.41	98.57
% Fe (total)	35.9	36.0	31.7	28.1	38.4	35.4	35.8	32.4	40.8	30.0	25.2	45.9
	25	26	27	28	29	30	31	32				
SiO ₂	52.7	44.3	32.6	50.20	60.63	49.69	47.54	51.94				
TiO ₂	0.00	0.06	0.08	0.15	tr	0.29	tr	tr				
Al ₂ O ₃	0.45	1.25	2.12	0.18	0.48	6.90	35.35	tr				
Fe ₂ O ₃	43.5*	52.0*	60.1*	37.84	25.10	8.74	13.54	32.67				
FeO				10.59	11.96	25.38	1.25	10.24				
MnO	0.15	0.20	0.09	0.06	0.19	0.13	0.05	0.06				
MgO	1.15	2.28	1.49	0.24	0.87	2.26	0.09	1.41				
CaO	0.24	2.15	0.10	0.31	0.17	5.42	0.94	2.76				
Na ₂ O	n.d.	n.d.	n.d.	0.04	0.04	0.14	0.05	0.07				
K ₂ O	0.13	0.77	0.78	0.05	0.07	0.06	0.05	0.06				
P ₂ O ₅	0.04	0.18	0.05	0.14	0.16	0.17	0.14	0.12				
Ignition loss	0.04	0.18	0.05	0.24	0.53	0.82	1.13	0.64				
H ₂ O				0.04	0.20	0.19	0.26	0.22				
Total	102.36	102.76	101.77	100.04	100.20	100.00	100.13	99.97				
% Fe (total)	30.4	36.3	42.00	34.7	26.8	25.8	10.5	30.8				

Analyses 1–21 and 28–32 are from *Ravich et al.* [1989]. Analyses 22–27 are from J. W. Sheraton, Bureau of Mineral Resources, Australia (determined by XRF by J. G. Pyke). Analyses 1–27, Mount Ruker, southern Prince Charles Mountains; 28–32, Vestfold Hills erratics; tr, trace; n.d., not determined.

*Total Fe as Fe₂O₃.

ple, estimating 32,028 million tons for the Hamersley Basin. Differences between the various estimates of reserves mostly stem from the different definitions of "reserves," "economic resources," and "resources" employed; however, it is clear that Australia has such vast iron ore resources that exploitation of the Mount Ruker banded iron formations is only a very remote possibility.

Other Exposures in the Prince Charles Mountains

Ravich *et al.* [1982] describe as jaspilites certain rocks from Mount Stinear on the north side of Fisher Glacier at its confluence with Lambert Glacier. These rocks contain less than 20% Fe and should not be classed as jaspilites (which by definition contain more than 25% Fe [Bates and Jackson, 1980]). Detailed mapping at Mount Stinear by Australian geologists has failed to reveal any outcrops that resemble the Mount Ruker banded iron formations, although such rocks were found as glacial erratics [Tingey *et al.*, 1981]. Although there are similarities between metasediments exposed at Mount Stinear and the Mount Ruker examples previously discussed, there are also marked differences, and therefore the sequences are not correlated by Tingey *et al.* [1981] and Tingey [1982a, b].

Subglacial Banded Iron Formations in the Prince Charles Mountains

Aeromagnetic surveys of the Prince Charles Mountains–Amery Ice Shelf area [Fedorov *et al.*, 1982] carried out by the Soviet Antarctic Expedition between 1972 and 1974 have revealed [Ravich *et al.*, 1982] two major, 5- to 10-km-wide, positive aeromagnetic anomalies extending westward from Mount Ruker for 120–180 km. Ravich *et al.* [1982] consider the anomalies to be subglacial extensions of the Mount Ruker banded iron formations. Ruker's [1963] report of hematite-rich boulders in moraines near Mount Scherger and Mount McCauley indicates that such rocks subcrop beneath the area's glaciers, but their economic potential can only be regarded as extremely small.

Enderby Land–Newman Nunataks

Lenticular, concordant bodies of magnetite-rich rock are quite common in the metasedimentary sequence of Enderby Land's Napier Complex. The largest exposed banded iron formation in Enderby Land is at Newman Nunataks (66°40'S, 54°45'E) and is described by Pieters and Wyborn [1977] as 750 m long and 150 m wide, the rock unit being about 20 m thick. Trail *et al.* [1967] also observed small bodies of similar rocks at outcrops now assigned to the Late Proterozoic Rayner Complex south of the Napier Complex in Enderby Land and nearby Kemp Coast.

The Napier Complex in Enderby Land is unusual in

that it contains rare mineral assemblages such as sapphirine and quartz, and osumilite on a regional scale [Sheraton *et al.*, 1980]. High-temperature, medium-pressure metamorphism with low partial pressures of water has been deduced by Dallwitz [1968], Sheraton *et al.* [1980], and Ellis *et al.* [1980], and geochronological and structural studies have revealed a complex geological history, including major high-grade metamorphic episodes at 3100 m.y., 2900 m.y., and 2400 m.y. [James and Black, 1981]. The Newman Nunataks banded iron formations are thus considered to be at least 3100 m.y. old and somewhat older than those described above at Mount Ruker.

The metamorphic grade at Newman Nunataks is considerably higher than that at Mount Ruker; the banded iron formations there are reddish brown to black, and they consist of folded bands of magnetite, dark gray to bluish pods of quartz, and various amounts of orthopyroxene [Pieters and Wyborn, 1977]. Rims of clinopyroxene and greenish, colorless, or blue clinoamphibole around hypersthene are interpreted as evidence for retrograde metamorphism, as is the presence, in two samples, of intergrown riebeckite and crocidolite in association with greenish and colorless amphibole. These retrograde effects may be related to the nearby stabilization of the Rayner Complex in Enderby Land and Kemp Coast about 1000 m.y. ago [Sheraton *et al.*, 1980].

Structure

Pieters and Wyborn [1977] describe small-scale generally tight to isoclinal and asymmetrical to recumbent folds and a superimposed large-scale open folding with a minimum wavelength of 200 m and expressed at the western peak by a shallow, eastward plunging synform in which banded iron formation overlies quartzofeldspathic gneiss.

Economic Considerations

Pieters and Wyborn [1977] list the iron content of 10 randomly collected specimens of Newman Nunataks banded iron formation; values range from 25.7% to 39.5% and average 34.4%, which is comparable to the Mount Ruker rocks. This iron content does not make the Newman Nunataks banded iron formation economically attractive, and although the outcrops are only about 70 km from the ice-bound Enderby Land coast, economic exploitation is inconceivable for the foreseeable future. Aeromagnetic surveys of Enderby Land by the Australian National Antarctic Research Expedition in conjunction with ice thickness profiling surveys did not detect extensive subglacial bodies of banded iron formation.

Vestfold Hills

Ravich [1960] describes erratic boulders of jaspilite from the Vestfold Hills and notes that they are particu-

larly common on the island in the center of Crooked Lake. He states that the jaspilites contain not less than 25% hematite, with quartz, and up to 10% of the clinopyroxene, salite. *Ravich et al.* [1982] note that the jaspilites were found, not only as great isolated lumps scattered over basement outcrops of the Vestfold Hills, but also as smaller, more numerous boulders concentrated in the coastal zone in terminal moraine deposits where they occur together with greenschist facies metasedimentary erratics. *Ravich et al.* [1982] continue: "the source of these ferruginous deposits is uncertain [but] it is tempting to assume that they may represent a subglacial inducer of an extensive zone of positive magnetic anomalies south of the Vestfold Hills [the distance is not stated]; this zone extends latitudinally for about 120 km and consists of a number of anomalies ranging from 10 to 40 km long, 2 to 4 km wide and 800–5900 gamma amplitude." Apparently, these magnetic anomalies are comparable to those near Mount Ruker, but their relationship to a narrow bedrock depression causes the Soviet authors to doubt whether these anomalies reflect the source of the jaspilite erratics. *Ravich et al.* [1982] also find it difficult to visualize the means of transport for the jaspilite debris from its possible source to its present location.

Regional geological considerations are of little use in locating the source of the Vestfold Hills jaspilite fragments, since a major east-west trending geologic discontinuity separates the Vestfold Hills (where Archean gneisses crop out) from the Rauer Islands 10 km to the south, where Late Proterozoic upper amphibolite to granulite facies gneisses are exposed [Tingey, 1982a]. The Late Proterozoic rocks, which characteristically do not contain banded iron formation, have been mapped at all outcrops on the Ingrid Christensen Coast southwest from the Rauer Islands, to the east flank of the Amery Ice Shelf, and into the northern Prince Charles Mountains. They are also continuous in a 500-km-wide east-west zone from the Rayner Complex in Enderby Land into Mac. Robertson Land and the Prince Charles Mountains and may well continue farther eastward. They are an improbable source of banded iron formation debris even though they typically contain a greater proportion of metasedimentary rock types (J. Sheraton, personal communication, 1984) than the predominantly igneous derived Archean gneisses of the Vestfold Hills.

Economic Considerations

Ravich et al. [1982] list analyses of four jaspilite specimens from the Vestfold Hills area (Table 1; analyses 28–32); iron contents range from 10.5% to 34.7%. If the rock with 10.5% iron is disregarded (it does not contain enough iron to warrant jaspilite classification), the average iron content is 20.5%. With such a modest iron content, these rocks cannot be regarded as eco-

nomically attractive. The presumably subglacial source of the fragments is unknown, but somewhere inland of the Vestfold Hills. Economic exploitation of such occurrences is exceedingly unlikely for many years.

Wilkes Land

Magnetite-rich rocks near the site of Wilkes Station in Vincennes Bay, Wilkes Land, are briefly reported by *Lovering and Prescott* [1979, p. 81]. The occurrences are obviously too small and remote to be of economic interest.

CONCLUSIONS

Banded iron formation crops out at a number of localities in Enderby Land and the Prince Charles Mountains and is reported as erratic blocks at several others [*Ravich et al.*, 1965; *Wright and Williams*, 1974]. Banded iron formations are common in basement shield areas of peninsular India, Western Australia, and South Australia that geologically resemble, and were once adjacent to, East Antarctica in the Gondwanaland reconstruction; it is therefore not surprising that such rocks occur in East Antarctica. However, the chances of banded iron formations being exposed in East Antarctica, which is about 97% ice covered, are not great. The biggest exposures, at Mount Ruker in the southern Prince Charles Mountains and Newman Nunataks in Enderby Land, are of banded iron formations that on average contain 34% Fe and have clearly not been affected by the near-surface enrichment processes that have converted banded iron formations of similar original iron content in India, Australia, and other countries into economically exploitable ore deposits. Thus while the occurrence of banded iron formations is to be expected in the East Antarctic metamorphic shield, their economic significance, for exploitative purposes, is minimal.

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COAL GEOLOGY, COAL QUALITY, AND COAL RESOURCES IN PERMIAN ROCKS OF THE BEACON SUPERGROUP, TRANSANTARCTIC MOUNTAINS, ANTARCTICA

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Permian coal beds occur within a fluvial sedimentary sequence in the Victoria Group of the Beacon Supergroup from the Ohio Range to northern Victoria Land, a 2000-km-long belt in the Transantarctic Mountains, Antarctica. Although coal beds as thick as 10.7 m have been reported, most beds are thinner than 2 m. Coal beds are generally lenticular, and exposure along strike is commonly not more than 1-3 km. In northern Victoria Land the Takrouna Formation contains coal in the small North Victoria Basin; in southern Victoria Land the larger South Victoria Basin contains the Weller Coal Measures; and the southernmost and largest basin, Nimrod-Ohio Basin, from the Nimrod Glacier to the Ohio Range, contains the Buckley Formation and its equivalents. One hundred forty-four published analyses of Permian coal from this region show that ash contents range from 3.2 to almost 50% with an arithmetic mean of 15.3%, and sulfur ranges from 0.0 to 4.8% with an arithmetic mean of 0.57%. Apparent rank of the coals ranges from high-volatile C bituminous coal to anthracite, but most of the coal samples have apparent ranks of low-volatile bituminous coal and semianthracite. The relatively high rank of much of the coal of the Transantarctic Mountains probably is related both to heat and pressure from sediment load and to heat from igneous intrusion; the dominant mechanism, however, remains to be determined. Paucity of data on coal thickness and distribution dictates that coal resource estimates be assigned to the hypothetical classification. Calculations based on published geologic maps, geologic descriptions, and measured sections indicate hypothetical resources of 3 billion metric tons in the North Victoria Basin, 50 billion metric tons in the South Victoria Basin, and 100 billion metric tons in the Nimrod-Ohio Basin.

INTRODUCTION

Much has been written over the past three decades about the presence of coal in Antarctica. Included has been speculation about the quantity and quality of the coal and whether this coal might legitimately be considered in the assessment of world energy resources. Coal occurs in widely spread locations on the Antarctic continent (Figure 1) and ranges in age from Permian to Tertiary. Although published reports from scattered localities describe coal beds as thick as 10.7 m, few reports have attempted to summarize available information and synthesize a coherent picture of what is known about the coal resources of Antarctica.

Wright and Williams [1974] show the areas of known coal-bearing rocks in Antarctica. *Spletstoesser* [1980] summarizes the stratigraphy of the coal-bearing Permian rocks in the Transantarctic Mountains and discusses in a general way the possibilities for utilization of Antarctic coal. *Kameneva and Mikhal'skiy* [1985] summarize the range of analyses of Permian coals from the Transantarctic Mountains and the Prince Charles Mountains. Their estimate of coal resources in limited areas

includes 6 billion metric tons in the Queen Alexandra Range in the central Transantarctic Mountains and 130 million metric tons in southern Victoria Land. No limit on depth of coal is specified.

The most complete discussion of coal in Antarctica of which we are aware is *Rose and McElroy's* [1987] paper "Coal Potential of Antarctica." Those authors show the localities of all major and most minor coal occurrences in Antarctica including Permian, Triassic, Jurassic (?), Cretaceous, and Tertiary coals. They summarize in tabular form the most important articles about each major area and present and discuss representative coal analyses from each area where analyses are available. Particularly useful is their bibliography of nearly a hundred references covering coal in all parts of the continent.

Rose and McElroy [1987] and *Whitby et al.* [1983] discuss some of the difficulties and limiting factors that face any attempt to exploit coal in Antarctica. Included are a unique ecosystem, long distances to markets, and the logistic and human problems involved in maintaining a small remote settlement, as well as the technological problems of working in a cold dry climate. Problems analogous in some ways have been faced in Spitzbergen,

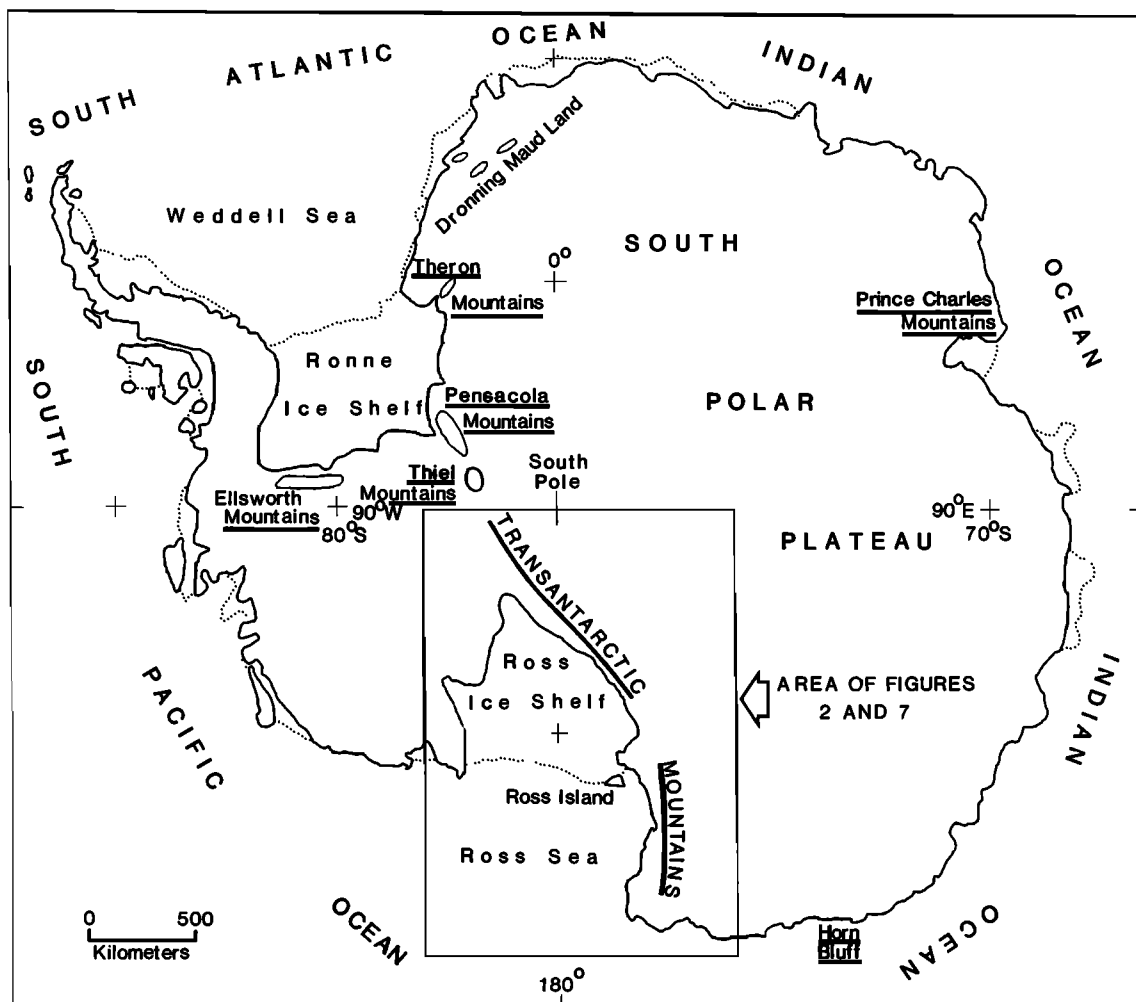


Fig. 1. Index map of Antarctica showing areas of Figures 2 and 7. Underlined place names indicate areas where Permian coal is reported by *Rose and McElroy* [1987].

where the Soviets and the Norwegians have been mining coal for many years. At Healy, Alaska, coal is mined in an open pit where winter weather conditions are similar to some Antarctic conditions. However, the situation is not analogous to Antarctica, as there is no permafrost and the summer temperature at Healy is as high as 80°F.

The most widespread exposures of coal-bearing rocks (coal measures), and the greatest known quantity of coal, occur in Permian fluvial rocks in three basins in the Transantarctic Mountains (Figure 2). The stratigraphic nomenclature as presently used (Figure 3) was summarized by *Elliot* [1975]. In this study we use the names for basins used by *Elliot* [1975]. The North Victoria Basin, the South Victoria Basin, and the Nimrod-Ohio Basin are shown in Figure 2.

The Transantarctic Mountains have undergone block faulting since deposition of the Beacon Supergroup, but

almost all of the Beacon rocks are unfolded. Attitudes range mostly from flat to 10 degrees of dip; dip directions are mostly toward the west and south beneath the cover of the ice cap of the polar plateau.

The purpose of the study reported here is to bring together and evaluate all published data on the distribution, quality, and quantity of Permian coal in the Transantarctic Mountains. To this end we have gone to the original sources for all published coal analyses in order to evaluate the effects of how samples were collected and handled, how analyses were performed, and how selectivity in choosing samples or reporting data may have biased reported results. Quantity of coal was estimated by using as much of the available data as possible, and methods of estimation are described.

Although coal beds are mentioned or described in many reports, most reports are concerned with geologic

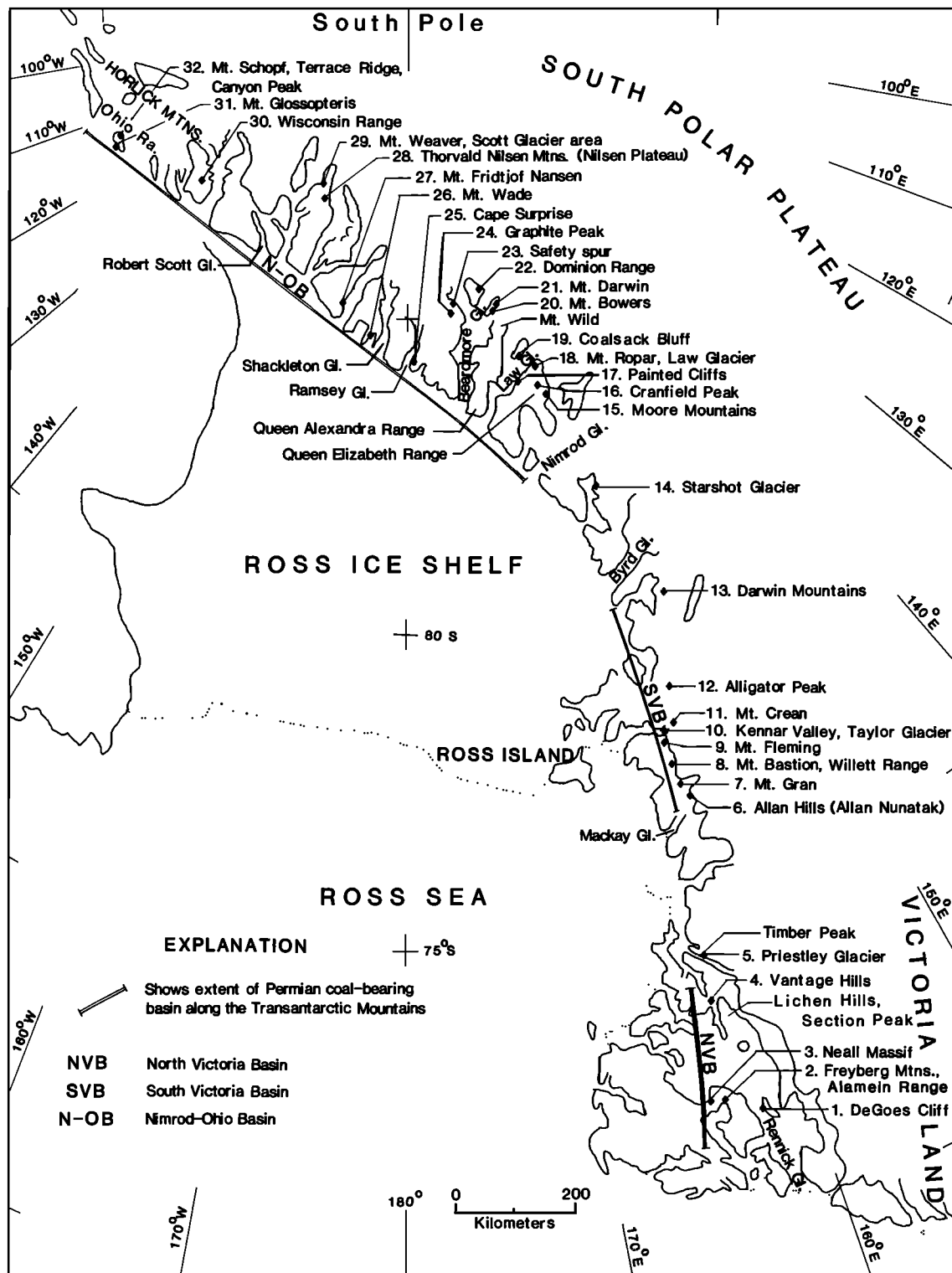


Fig. 2. Map of the Transantarctic Mountains showing locations of selected measured sections of Permian coal measures and extent of basins of Permian coal sedimentation. Information on coal measures at numbered localities is summarized in Table 1.

Long, 1965a; Frakes et al., 1971	Minshaw, 1966; 1967	Doumani and Minshaw, 1965; Minshaw, 1967	Long, 1965b; Coates, 1985	Barrett, 1965; Coates, 1985	LaPrade, 1970; Kitching et al., 1972	Barrett, 1972; Elliot, 1970	Barrett, 1972; Elliot, 1970; Lindsay, 1970	Barrett, 1972; Lindsay, 1970; Coates, 1985	Laird et al., 1971
Ohio Range	Wisconsin Range	Scott Glacier	Nilsen Plateau	Mt Fridtjof Nansen	Shackleton Glacier	Dominion R. to Otway Massif	Queen Alexandra Range	Queen Elizabeth Range	Nimrod Gl.
NIMROD-OHIO BASIN									
						Kirkpatrick Basalt 425+ m	Kirkpatrick Basalt 500+ m		
						DISCONFORMITY(?) Prebble Fm. 460 m	DISCONFORMITY(?) Prebble Fm. 3-148 m		
						DISCONFORMITY(?) Falla Fm. 200+ m	DISCONFORMITY(?) Falla Fm. 160-530 m		
			Nilsen Fm. 180 m Disconformity(?)		Falla Fm. 200+ m Fremouw Fm. 700 m DISCONFORMITY	Falla Fm. 200+ m Fremouw Fm. 750 m DISCONFORMITY(?)	Falla Fm. 160-530 m Fremouw Fm. 650 m DISCONFORMITY(?)	Fremouw Fm. 150 m DISCONFORMITY(?)	
Mount Glossop Fm. 750 m	Queen Maud Fm. 25+ m	Queen Maud Fm. 600 m	Queen Maud Fm. 95m-195 m	Unit C 260+ m	Buckley Fm. 450 m	Buckley Fm. 300+ m not exposed	Buckley Fm. 750 m	Buckley Fm. 650+ m	Buckley Fm. 420+ m
						Fairchild Fm. 200 m	Fairchild Fm. 130-220 m	Fairchild Fm. 250 m	
Discovery Ridge Fm. 195 m	Upper Mbr. 125 m Middle Mbr. 220 m Lower Mbr. 85 m	Upper Mbr. 70-150 m Middle Mbr. 70-125 m Lower Mbr. 10-75 m	Amundsen Fm. 100-270 m	Unit B 195 m	Mackellar Fm. 160 m		Mackellar Fm. 60-90 m	Mackellar Fm. 60-140 m	Mackellar Fm. 13-115 m
Buckeye Fm. 308 m	Buckeye Fm. 56 m	Scott Glacier Fm. 0-20 m	Scott Glacier Fm. 0-93 m	Basal Cgl. 0-3 m	Pagoda Fm. 4-190 m		Pagoda Fm. 126-175 m	Pagoda Fm. 136-435 m	Pagoda Fm. 60-200 m
DISCONFORMITY	UNCONFORMITY	UNCONFORMITY	UNCONFORMITY	UNCONFORMITY	UNCONFORMITY		DISCONFORMITY	UNCONFORMITY	DISCONFORMITY
Horlick Fm. (L. Devonian) UNCONFORMITY							Alexandra Fm. UNCONFORMITY		Alexandra Fm. Castle Crags Fm. UNCONFORMITY

Fig. 3. Stratigraphic correlation of the Victoria Group of the Beacon Supergroup from

exploration and stratigraphy rather than with coal per se. Accordingly, the number of reports that are truly useful in the study of coal is limited. In the remainder of this paper we try to guide the reader's attention to the most useful of these.

STRATIGRAPHY

The Permian coal measures in the Transantarctic Mountains are within a typical Gondwana sedimentary sequence called the Victoria Group, which is the upper unit in the Devonian to Triassic Beacon Supergroup (Figure 3). The Victoria Group lies on a widespread, regionally very flat unconformity, which is called the Maya erosion surface in the type area of the Beacon Supergroup in southern Victoria Land and southward to the Scott Glacier area. In northern Victoria Land it is known as the Sub-Beacon Surface [Walker, 1983], and south and east of Scott Glacier this unconformity is not named. Minshaw [1966] recognized an erosion surface in the Wisconsin Range (Figure 2, location 30) but did not name it. Long [1965a] described a similar surface with a maximum relief of 68 feet (21 m) in the Ohio Range (Figure 2, locations 31 and 32); in his discussion he compared it to the Maya erosion surface of Gunn and Warren [1962] but stopped short of applying the name Maya to the erosion surface in the Ohio Range.

In most areas the basal sediments in the Victoria Group are glacial deposits [Elliot, 1975; Coates, 1985]. Overlying the glacial deposits, the Ohio Range west and north to the Nimrod Glacier area, are lake deposits, the Mackellar Formation (Permian) and its

equivalents (Figure 4). Above this lie the Fairchild Formation (Permian) and its equivalents, a sequence of fluvial sandstones, shales, and in a few areas conglomerates, above which lie the Permian coal measures. Above the Permian coal measures are Triassic fluvial sediments of the Fremouw Formation and the Falla Formation [Elliot, 1975], which contain no coal in most places, but increasing amounts of volcanogenic sediments. The youngest formation in the Victoria Group is the Triassic Prebble Formation consisting largely of lahar debris, pyroclastic breccia, tuff, and tuffaceous sandstone, all of intermediate to acidic composition [Barrett and Elliot, 1972].

In the Jurassic the Beacon Supergroup was intruded by dolerite sills and dikes, the Ferrar Dolerite, which thermally metamorphosed many of the immediately adjacent rocks and caused widespread low-grade alteration throughout the sequence. Coals in the Victoria Group, having been heated to varying degrees, range from high-volatile bituminous to anthracite and even graphite in some places. The extrusive phase of the Ferrar Dolerite is the Kirkpatrick Basalt, which overlies the Prebble Formation [Faure et al., 1972].

Because exploration and geologic studies were undertaken at scattered places and times, the stratigraphic nomenclature through the length of the Transantarctic Mountains grew quite complex by the late 1960s. Since that time, several authors, notably McKelvey et al. [1970, 1972], Barrett et al. [1971], and Barrett [1972], have undertaken the task of consolidating stratigraphic nomenclature. Elliot [1975] provided a systematic sum-



In each area of coal measures we have tried to use the stratigraphic names applied by the latest author(s) to work in the area. This still leaves no less than seven stratigraphic names for Permian coal measures in three

basins, all of which appear to be correlative. The following discussion starts in the North Victoria Basin in northern Victoria Land, proceeds through the South Victoria Basin, then progresses the length of the Nimrod-Ohio Basin (Figure 2). Information on representative occurrences of coal measures is summarized in

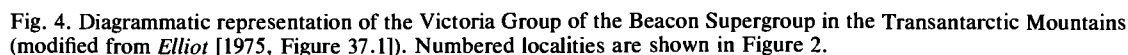


Table 1. Locations referred to by number in Table 1 and elsewhere in this paper are shown in Figure 2.

North Victoria Basin

Coal-bearing rocks in the North Victoria Basin (Figure 2) were first described by *Dow and Neall* [1972, 1974]. In the Freyberg Mountains (Figure 2, location 2) they defined the Takrouna Formation at Takrouna Bluff where they described 60 m of flat-lying, cyclically bedded sandstones, siltstones, and shales containing sparse coal beds as thick as 3 m and fossil leaves of the Permian tree *Glossopteris*. At the type locality the formation lies on the Sub-Beacon Surface. This erosion surface, correlative with the Maya erosion surface, is developed on deeply weathered Granite Harbor Intrusives of Cambrian and Ordovician age. The top of the Takrouna Formation was not seen, and its original thickness could not be determined.

Correlation between outcrops of the Takrouna is difficult because they are widely separated through a large region and both vertical and lateral facies changes are common. *Walker* [1983] defined two facies associations: facies association 1 is dominated by tabular sheet sandstone beds and contains features indicating low-sinuosity braided streams; facies association 2 is dominated by ripple- and parallel-laminated sandstones and other structures indicating low-sinuosity streams and no indication of braiding. Within this second association is the coal facies, which includes coaly shale, coal, green siltstones, and sandstones that fine upward. The two facies associations were not found anywhere in the same outcrop, and thus *Walker* was unable to determine their stratigraphic relationship.

The age of the Takrouna Formation is uncertain. *Gair et al.* [1965] and *Norris* [1965] identified assemblages of miospores and acritarchs from Section Peak (Figure 2) as being of "probable Upper Triassic" age. *Collinson and Kemp* [1983] accept this age and on that basis suggest that all of the Takrouna Formation along the margin of the polar plateau is Triassic. Farther north, on the basis of microflora, G. Norris, in the work of *Sturm and Carryer* [1970], assigned a Triassic age to basal Takrouna sediments in the Freyberg Mountains. However, *Walker* [1983], in discussing this area, emphasizes an abundant and widespread Permian *Glossopteris* flora in the Takrouna Formation and for this reason questions the Triassic age assigned by *Norris* and considers at least the lower part of the Takrouna to be Permian. The Takrouna apparently includes both Permian and Triassic rocks; further work will be needed to determine the age of specific parts of the formation.

The thickest sections of the Takrouna Formation are reported by *Collinson and Kemp* [1983] in the Rennick Glacier area: 285 m in the northern Alamein Range, and 280 m at DeGoes Cliff in the Freyberg Mountains

(Figure 2, location 2). Neither measurement represents the original thickness, as erosion has removed the top of both stratigraphic sections. To the west and south, in the Lichen Hills and Vantage Hills along the margin of the polar plateau (Figure 2) *Collinson and Kemp* [1983] report only 25–40 m of Takrouna Formation and conclude that this area is near the basin margin. Farther south, at Priestly Glacier, *Skinner and Ricker* [1968] found no Takrouna or equivalent. These findings are consistent with a southward thinning trend and with the interpretation of a divide between the depositional basin of the Takrouna Formation and that of the Weller Coal Measures in southern Victoria Land.

Collinson and Kemp [1983, p. 223] conclude that the Takrouna Formation was deposited in an "elongate northwest trending basin that developed during the latest Carboniferous." On the basis of changes in facies and preserved stratigraphic thickness, they infer that the western margin of the basin lay not far west of the edge of the polar plateau and the eastern margin not far east of the Freyberg Mountains. Both *Collinson and Kemp* [1983] and *Walker* [1983] found that sedimentary structures show the main sediment transport directions to be north and west.

Faulting was active during deposition of the Takrouna Formation at DeGoes Cliff as well as later in other parts of the basin [*Walker*, 1983]. Rocks of this basin have been disrupted by several faults, but most of the Beacon rocks are nearly flat lying.

South Victoria Basin

In the South Victoria Basin (Figure 2) the Permian coal-bearing rocks are now generally known as the Weller Coal Measures, although several other names have been used in the past (Table 1). In most localities the Weller Coal Measures lie disconformably on glacial deposits within the Victoria Group along what *McKelvey et al.* [1970] have called the Pyramid erosion surface (Figure 3). At Mount Gran (Figure 2, location 7) the coal measures overlie the Taylor Group [*Mirsky et al.*, 1965] on the Maya erosion surface.

Recent authors [e.g., *Elliot*, 1975; *Barrett and Kohn*, 1975; *Rose and McElroy*, 1987] consider the entirety of the Weller Coal Measures to be Permian, although *Matz et al.* [1972] put the Permian-Triassic boundary within the unit. *Spletstoeser* [1980] has placed the Weller in the middle Permian, slightly older than the Buckley Formation farther south. For the purposes of this study we consider the entire unit to be Permian. The Weller Coal Measures, as presently defined, are generally no more than 200–250 m thick. They are mostly fine- to coarse-grained sandstones that were deposited in a fluvial environment [*Barrett and Kohn*, 1975; *Rose and McElroy*, 1987].

The configuration of the basin in which the Weller

Coal Measures were deposited is poorly known. On the basis of paleocurrent indicators, *Barrett and Kohn* [1975] found in the basal 80 m of the formation a "watershed," north of which the paleocurrents were largely northwestward, and south of which they were mostly southeastward. These authors reach no satisfactory interpretation of the "watershed." Higher than 80 m above the base of the formation, paleocurrents were dominantly southward and southeastward. Variability of paleocurrent direction is large enough to suggest high-sinuosity streams, although the sediments are coarse and in some places conglomeratic. *Barrett and Kohn* [1975, p. 29] conclude: "Control of stream direction by the ice margin, and by an irregular hummocky topography exposed by the retreating ice sheet, must have contributed substantially to paleocurrent variability." On the basis of thickness distribution and paleocurrent data, they conclude that the source of the sediments in the Weller Coal Measures lay to the east, in the position of the present Ross Ice Shelf. The orientation of paleoflow to northwest and southeast implies that deposition was constrained within a linear subsiding basin, but the eastern and western limits of the basin are not known. Coal beds, although as thick as 7 m [*Barrett and Kohn*, 1975], are not laterally continuous. They generally cannot be correlated between outcrops, and beds are commonly seen to thin or pinch out in short distances laterally.

The quantity of coal in the Weller Coal Measures decreases southward [*Rose and McElroy*, 1987]. At Allan Hills ("Allan Nunatak," Figure 2, location 6), *Schopf and Long* [1966] report an aggregate thickness of 10–12 m of coal, and at Mount Gran (Figure 2, location 7) *Mulligan et al.* [1963a] report 8.5 m. Coal beds in this region are reported as thick as 6 m, at Allan Hills, and thicker than 2 m at several localities (Table 1).

Farther south, in the Darwin Mountains (Figure 2, location 13; Figure 4), the thickest coal bed documented in the Misthound Coal Measures is 20 cm [*Haskell et al.*, 1965]. The Misthound Coal Measures, which are correlated with the Weller Coal Measures, contain some thin carbonaceous sandstones and shales as well, but the paucity of coal confirms the southward diminution of coal occurrence.

At Starshot Glacier (Figure 2, location 14), *Skinner* [1964, 1965] describes 235 m of gently dipping rocks of the Beacon Supergroup lying unconformably on steeply dipping Shackleton Limestone (Cambrian). The Beacon strata are probably part of the Victoria Group, but their stratigraphic position is not known. No coal is reported, and in this region the Victoria Group seems devoid of coal.

Nimrod-Ohio Basin

From the Nimrod Glacier south and east to the Ohio Range the basal unit of the Victoria Group is the

glacially derived Pagoda Formation and its equivalents, which lie on a widespread, regionally very flat erosion surface. The sequence progresses upward, without major interruption, through lacustrine facies (Mackellar Formation and equivalents), non-coal-bearing fluvial facies (Fairchild Formation and equivalents), and coal-bearing fluvial facies (Buckley Formation and equivalents). Figure 4 shows this relationship diagrammatically, and Figure 3 shows the nomenclature of stratigraphic units through the region.

The Buckley Formation and its equivalents apparently represent a laterally continuous fluvial facies aggrading in a linear basin nearly parallel to the present trend of the Transantarctic Mountains. The Buckley Formation from the Queen Elizabeth Range to Mount Fridtjof Nansen is described by *Barrett* [1965, 1969, 1972] and *LaPrade* [1970]. Much of the Buckley consists of fining upward sequences grading from conglomeratic sandstone overlying a scoured surface upward into arkosic sandstone and then siltstone and shale and occasionally coal. Many of the sandstone units contain trough cross-bedding in sets 15–60 cm thick [*Barrett*, 1969]. Ripple cross-lamination and climbing ripples are common in the finer beds. *Barrett* [1969] interprets the Buckley Formation as the product of deposition on a slowly subsiding floodplain supplied by meandering streams and having ephemeral lakes and swamps in which beds of fine sediments were deposited and peats accumulated. *Isbell* [1988], on the basis of configuration of sandstone bodies and other sedimentary features, concluded that the streams were braided. The coal beds generally are discontinuous, which is common in a fluvial depositional environment [*Fielding*, 1985].

The Buckley Formation is best exposed and best studied in the region between the northern part of the Queen Elizabeth Range and the upper Ramsey Glacier (Figure 2). In that area, *Barrett* [1969] measured 17 stratigraphic sections that included Buckley Formation. By combining two nearby sections, he documented a total thickness of 745 m. Because no single section contained both upper and lower contact, he could not determine the maximum thickness in the region or the range in thickness. At Mount Wild in the southern Queen Alexandra Range (Figure 2, between locations 19 and 20), *Barrett* found at least 10.7 m of total coal in the Buckley Formation, including one bed 8.5 m thick. Also, several beds of graphite as thick as 3 m in a brecciated area intruded by dolerite indicate that some coal has been thermally metamorphosed. *Barrett* found that coal commonly makes up 3–6% of the middle and upper parts of the Buckley in this region. Although the rocks have undergone some normal faulting, most of the beds are undeformed and are flat lying or dip gently to the southwest.

At Cape Surprise on the edge of the Ross Ice Shelf (Figure 2, location 25), *Barrett* [1965] describes two

TABLE 1. Information on Selected Published

Location No.	Reference	Locality	Unit Name	Latitude	Longitude
North Victoria Basin					
1	<i>Walker [1983]</i>	DeGoes Cliff	T.Fm.	71°44'S	162°00'E
2	<i>Dow and Neall [1974]</i>	Freyberg Mountains	T.Fm.	71°59'S	163°24'E
3	<i>Collinson and Kemp [1983]</i>	Neall Massif	T.Fm.	72°04'S	164°28'E
4	<i>Collinson and Kemp [1983]</i>	Vantage Hills	T.Fm.	73°33'S	162°27'E
Between Basins					
5	<i>Skinner and Ricker [1968]</i>	Priestley Glacier	...	74°20'S	164°22'E
South Victoria Basin					
6	<i>Gunn and Warren [1962]</i>	Allan Nunatak	G.Ss.	76°45'S	159°40'E
6	<i>Schopf and Long [1966]</i>	Allan Nunatak	W.C.M.	76°45'S	159°40'E
6	<i>Townrow [1967]</i>	Allan Hills	W.C.M.	76°45'S	159°40'E
6	<i>Ballance [1977]</i>	Allan Hills	W.C.M.	76°45'S	159°40'E
7	<i>Mulligan et al. [1963a]</i>	Mount Gran	B.-S.	76°59'S	160°58'E
7	<i>Schopf and Long [1966]</i>	Mount Gran	W.C.M.	76°59'S	160°58'E
7	<i>Schapiro and Gray [1966]</i>	Mount Gran	W.C.M.	76°59'S	160°58'E
8	<i>Allen [1962]</i>	Mount Bastion	M.B.C.M.	77°19'S	160°30'E
8	<i>Korsch [1974]</i>	Mount Bastion	W.C.M.	77°19'S	160°30'E
8	<i>Mulligan et al. [1963b]</i>	Willett Range	W.Fm.	77°09'S	160°25'E
9	<i>Whitby et al. [1983]</i>	Mount Fleming	W.C.M.	77°33'S	160°25'E
9	<i>McKelvey et al. [1977]</i>	Mount Fleming	W.C.M.	77°33'S	160°08'E
10	<i>Whitby et al. [1983]</i>	Kennar Valley	W.C.M.	77°45'S	160°15'E
10	<i>McKelvey et al. [1977]</i>	Kennar Valley	W.C.M.	77°45'S	160°15'E
11	<i>Kyle [1976]</i>	Mount Crean	W.C.M.	77°54'S	159°28'E
12	<i>McKelvey et al. [1977]</i>	Aligator Peak	W.C.M.	78°28'S	158°43'E
13	<i>Haskell et al. [1965]</i>	Darwin Mountains	M.C.M.	79°46'S	156°10'E
Between Basins					
14	<i>Skinner [1964, 1965]</i>	Starshot Glacier	...	81°20'S	160°20'E
Nimrod-Ohio Basin					
15	<i>Barrett [1969]</i>	Moore Mountains	B.Fm.	83°21'S	160°30'E
16	<i>Barrett [1969]</i>	Cranfield Peak	B.Fm.	83°38'S	160°55'E
17	<i>Barrett [1969]</i>	Painted Cliffs	B.Fm.	83°30'S	162°20'E
18	<i>Barrett [1969]</i>	Mount Ropar	B.Fm.	83°58'S	160°29'E
18	<i>Schopf and Long [1966]</i>	Law Glacier area	B.Fm.	84°S	159°30'E
19	<i>Elliot et al. [1972]</i>	Coalsack Bluff	B.Fm.	84°14'S	162°25'E
20	<i>Young and Ryburn [1968]</i>	Mount Bowers	B.C.M.	85°00'S	164°05'E
20	<i>Young and Ryburn [1968]</i>	Mount Bartlett	B.C.M.	84°56'S	163°56'E
21	<i>Young and Ryburn [1968]</i>	Mount Darwin	B.C.M.	85°02'S	163°08'E
22	<i>Schopf and Long [1966]</i>	Dominion Range	B.Fm.	85°05'S	171°30'E
23	<i>McGregor [1965]</i>	Safety Spur	D.C.M.	85°19'S	168°00'E
24	<i>McGregor [1965]</i>	Graphite Peak	B.C.M.	85°03'S	172°43'E
24	<i>Barrett [1969]</i>	Graphite Peak	B.Fm.	85°03'S	172°43'E
25	<i>Barrett [1965]</i>	Cape Surprise	Unit C	84°31'S	174°25'W
26	<i>Barrett [1965]</i>	Mount Wade	Unit C	84°51'S	174°15'W
27	<i>Barrett [1965]</i>	Mount Fridtjof Nansen	Unit C	85°21'S	167°33'W
28	<i>Schopf and Long [1966]</i>	Thorvald Nilsen Mountains	...	86°20'S	158°00'W
29	<i>Doumani and Minshew [1965]</i>	Scott Glacier area	Q.M.Fm.	87°S	153°30'W
29	<i>Schopf and Long [1966]</i>	Mount Weaver	...	87°S	153°30'W
30	<i>Minshew [1966, 1967]</i>	Wisconsin Range	Q.M.Fm.	85°45'S	125°00'W
31	<i>Long [1965a]</i>	Terrace Ridge	M.G.Fm.	84°48'S	113°25'W
31	<i>Schopf and Long [1966]</i>	Mount Schopf	G.Fm.	84°48'S	113°25'W
31	<i>Schopf and Long [1966]</i>	Canyon Peak	G.Fm.	84°50'S	114°W
31	<i>Schapiro and Gray [1966]</i>	Ohio Range	M.G.Fm.	84°48'S	113°25'W
32	<i>Long [1965a]</i>	Mount Glossopteris	G.Fm.	84°44'S	113°43'W
32	<i>Schopf and Long [1966]</i>	Mount Glossopteris	G.Fm.	84°44'S	113°43'W

Three dots indicate that this information is not included in the source. For map locations, see Figure 2. Stratigraphic names are abbreviated as follows: B.C.M., Buckley Coal Measures; B.Fm., Buckley Formation; B.-S., Beacon-Sage Group; D.C.M., Dominion Coal Measures; G.Fm., Glossopteris Formation; G.Ss., Glossopteris Sandstones; M.B.C.M., Mount Bastion

Permian Coal Localities in the Transantarctic Mountains

Thickness of Section, Meters	Coal Aggregate Thickness, Meters	Thickest Coal Bed, Meters	Analyses Original or Reprinted	Lateral Extent of Coal	Comments
North Victoria Basin					
270	4±	1.5-2	...	...	3 coal beds; thickness estimated on section.
60+	...	3+	original	80 km²	High-volatile bituminous.
230	0	0	...	0	Near east margin of Takrouna basin.
28	0	0	...	0	South end of Takrouna basin.
Between Basins					
0	0	0	...	0	No Permian present.
South Victoria Basin					
105	...	2.5	original	...	Coals thin westward.
...	10-12	6	original	10 km²	
35	...	...	...	1-2 km²	
80	...	3	...	1 km	
460	8.5	4.5	original	1 km	
...	...	...	original	...	Map of Allan Nunatak shows Triassic and Permian. Banded anthracites and semianthracites.
...	...	...	reprinted	...	
900	...	1	original	...	40 coal horizons in basal 160 m of section.
205	...	<0.15	...	...	Semianthracite.
65	12	2.4	original	...	
...	...	1.6	original	...	22 measured sections of Weller Coal Measures in the area; 7 are complete sections.
98-186	7+	7	...	150 m	
...	...	2.6	original	...	Ph.D. dissertation on paleobotany, cited by <i>Rose and McElroy</i> [1987].
72-232	...	1	...	...	
...	...	...	original	...	Incomplete section north of Alligator Peak.
57+	...	...	...	...	
93	...	20 cm	...	...	
Between Basins					
0	0	0	...	0	235-m section, probably Victoria Group; no coal.
Nimrod-Ohio Basin					
95+	1	1	original	...	At 15, 16, 17, 18, thickness was estimated by measuring on drawn stratigraphic sections.
260+	2	1	original	...	
540	15	10.7	...	...	3 coal beds shown in section.
420+	11.5	3.8	original	...	
...	...	...	original	...	3 coal beds shown on section.
750±	>10-20	10	...	...	
320+	...	1.5	...	...	7 seams, bright bituminous or anthracite.
120+	...	3.7	...	1 km²?	1 coal bed, 2-3.7 m, nearly circles mountain.
190+	...	...	...	...	Thicknesses estimated from drawn stratigraphic sections.
...	...	3	original	...	
250+	13	5	...	...	Bed has shaly partings.
...	...	9	...	...	
295+	...	6+	original	...	2 coal beds shown on section.
292	24	6	...	...	11 coal beds; most coal is shaly; coal thicknesses estimated from stratigraphic sections.
253	...	...	...	...	No coal reported.
260	6	6	...	...	Coaly shale and fissile coal.
...	...	...	original	...	32 coal beds.
432	15+	7.6	...	...	
...	...	...	original	...	26 analyses original, 4 from <i>Blackburn</i> [1937].
25	0	0	...	0	
...	...	...	...	...	Only basal sandstone of Q.M.Fm. contain quartz pebbles.
700	23	3.7	original	1.2 km	
...	...	...	original	...	Location approximate.
...	...	...	original	...	
...	...	...	both	...	Mount Glossopteris and Mount Schopf.
700	23	3.8	...	12,000 m	Low-volatile bituminous to semianthracite.
...	...	...	original	...	

Coal Measures; M.C.M., Misthoun Coal Measures; M.G.Fm., Mount Glossopteris Formation; Q.M.Fm., Queen Maud Formation; T.Fm., Takrouna Formation; W.Fm., Weller Formation; and W.C.M., Weller Coal Measures.

blocks of tilted, downfaulted Beacon strata that include a coal-bearing interval that Barrett designates unit C. He calculated that faulting has dropped the rocks in this area 3000–5000 m in relation to the Beacon rocks in the mountains 50–80 km to the west and southwest (Figure 2). In all measured sections in unit C, paleocurrent directions are dominantly southeastward, consistent with paleocurrents in the Buckley Formation to the south and west of Cape Surprise.

At Mount Wade and Mount Fridtjof Nansen (Figure 2, locations 26 and 27), the Victoria Group extends upward from glacial deposits lying on the Maya erosion surface through coal measures. Barrett [1965] designates the coal measures unit C and correlates the unit with the Buckley Formation, which crops out in the mountains to the northwest and to the south and east. Unit C is about 260 m thick and contains several coal beds.

At Nilsen Plateau and Mount Weaver (Figure 2, locations 28 and 29), Doumani and Minshew [1965] refer to the coal measures as unit E and correlate them with the Buckley Formation in the Beardmore Glacier area (Figures 2 and 3). They assign a thickness of 432 m. Minshew [1966], in discussing the Wisconsin Range, uses the name Queen Maud Formation for the coal measures both there and in the Scott Glacier area, which includes the Nilsen Plateau and Mount Weaver. In this context he assigns a thickness of 600 m to the Queen Maud Formation in the Scott Glacier area.

In the Wisconsin Range (Figure 2, location 30), Minshew [1966] found only 25 m of the Queen Maud Formation in flat-lying sediments of the Victoria Group. The lowest member of the Victoria Group is the Buckeye Formation (Figures 3 and 4), which is of glacial origin. Overlying it is the Weaver Formation, consisting of interbedded siltstone and shale, which contain trace fossils. The upper member of the Weaver Formation is sandstone, which contains animal burrows, overlain by a *Glossopteris*-bearing shale. Overlying the Weaver Formation is cross-bedded sandstone, 25 m thick, containing numerous small beds and lenses of rounded pebbles of grayish quartz. On the basis of stratigraphic position and the presence of quartz pebble beds, Minshew [1966] considers this unit to be the basal Queen Maud Formation. The sequence is truncated by the present erosion surface, and there is no way to determine the original thickness of the Queen Maud Formation in this region. Coal is not reported here.

The Ohio Range (Figure 2, locations 31 and 32) was a site of some of the early studies of coal in Antarctica [Schopf and Long, 1966; Long, 1962, 1964a, b, 1965a]. The coal measures, called the Mount *Glossopteris* Formation, are well exposed in several places and are as thick as 700 m. Long [1965a, p. 102] reports “a total of 76 feet (23 m) of coal and impure coal in beds 4–12 feet (1.2–3.5 m) thick.” The proportion of coal to impure

coal is not specified. An adit was driven into the lowest coal bed on Terrace Ridge at Mount Schopf (Figure 2, location 32) in order to obtain samples for analysis from coal deeper and less weathered than the outcrop.

The lateral extent of individual coal beds appears to be greater on Terrace Ridge than in other parts of the Transantarctic Mountains; Long [1965a] reports that most of the beds are continuous for some 4000 feet (1200 m) across the exposed slope. Nonetheless, on the next ridge to the northeast, 2 km away, some of the coal beds are missing. On the basis of study throughout the Ohio Range, Long [1965a, p. 103] came to assume that “. . . coal seams are more or less lenticular and may not be continuous over distances greater than a mile or two.”

COAL QUALITY

Coal samples are collected, analyzed, and tested in order to characterize a coal. Reliable chemical and physical characterization of the coal as it exists in its natural, in-place state is necessary to understand its geologic history and predict its economic potential. Factors affecting economic potential include amount of coal available for recovery, transportation and storage characteristics, heat of combustion, rank, percentages of sulfur and ash, and evaluation of possible utilization. Creating a reliable set of data to characterize the coal depends on adherence to standard philosophy, methodology, and technology. The sequence begins with the decision to collect a sample and ends with attempts to interpret the results of chemical analyses and physical tests. Over the years, Antarctic coals have been collected applying a great variety in philosophy, techniques, and handling; laboratory analyses and determinations and use of data have not been standard. For these reasons the data available are not as useful as they could be.

Proximate analysis of coal includes determination of moisture, volatile matter, and ash and calculation of fixed carbon [American Society for Testing and Materials, 1986, D3172–73, p. 401]. Determination of sulfur content of the coal conventionally is done along with proximate analysis, and heat of combustion of the coal (in British thermal units per pound) is determined in almost all cases.

The moisture content of coal is critical in evaluating the coal for utilization. Moisture in coal is defined in two forms. Inherent moisture is moisture that is part of the coal in its natural state, including moisture in pores but not that in visible fractures. Total moisture is defined by the loss in weight in air under rigidly controlled conditions of temperature, time, and air flow [American Society for Testing and Materials, 1986, D3302]. Moisture reported in proximate analyses is total moisture.

Volatile matter is defined as “. . . those products, exclusive of moisture, given off by a material as gas or

vapor, determined by definite prescribed methods . . ." [*American Society for Testing and Materials*, 1986, D121-85, p. 214]. Volatile matter is important because it is used in determining rank and in predicting coking properties.

Ash is the inorganic residue remaining after combustion of the coal. Quantity (percent) and composition of ash are important in coal utilization. In the analyses discussed below only ash percentages are reported.

Fixed carbon percentage is calculated by subtracting the determined percentages of moisture, volatile matter, and ash from 100. Fixed carbon is used in determining rank.

Ultimate analysis includes determination of hydrogen, carbon, nitrogen, sulfur, oxygen, and ash [*American Society for Testing and Materials*, 1986, D3176-84, p. 414]. This analysis provides a uniform system for comparison of coals and cokes and a basis for cursory evaluation of these materials.

Although the Transantarctic Mountains contain many coal beds, good quality data are meager. Analyses of 144 Permian coal samples have been reported from 19 areas over a distance of 2000 km. Most Permian coal samples from Antarctica have been collected from outcrops, or in some cases talus, because the lack of artificial exposures, such as mines, precludes sampling in accordance with standard methods [*Schopf*, 1960]. No core samples of Antarctic coals have been reported. The following tables report data available for coal beds in the Transantarctic Mountains from northern Victoria Land to the Ohio Range. Apparent rank was determined using the Parr formulas for moist, mineral-matter-free Btu and dry, mineral-matter-free fixed carbon according to American Society for Testing and Materials (ASTM) Standards [*American Society for Testing and Materials*, 1986, D388-84, p. 249]. The following sections present coal analysis data in geographic sequence from northern Victoria Land to the Ohio Range. Location numbers refer to Figure 2 and Table 1.

North Victoria Basin

Freyberg Mountains (location 2). *Dow and Neall* [1974] report proximate analyses of two coal samples (Table 2) from the Takrouna Formation at Neall Massif, Freyberg Mountains. The coal beds are 3 m (sample 13/433) and 1.8 m (sample 13/434) thick. Sampling method was not described. These coals are of low rank compared with other Antarctic coals. *Dow and Neall* attributed this to the coal's being more than 1 km from any observed dikes or sills. One of the samples has an apparent rank of high-volatile C bituminous coal.

South Victoria Basin

Allan Hills (location 6). *Gunn and Warren* [1962, p. 109] report proximate analyses (Table 2) for two sam-

ples. They note that the coals have been severely baked by nearby dolerite sills. *Schopf and Long* [1966, pp. 177, 178] report the proximate and ultimate analyses (Table 2) for two samples which were collected by Long. Sample CGL-259 is a composite sample from a 5.8-m bed. *Schopf and Long* [1966, p. 160] published only analyses in which the coal ash content was 20% or less. They do not report how many samples contained more than 20% ash.

Mount Gran (location 7). *Schopf and Long* [1966] reported on four samples (Table 3) with ash content of 20% or less which were collected by P. E. Calkin in 1960. Type and method of sampling are not described. *Mulligan et al.* [1963a] collected 17 samples at Mount Gran and sealed them in screw-top cans and jars; of these, two samples were lost, and six samples contain more than 50% ash and therefore are not coal and are not reported here. Analyses of the remaining nine samples are included in Table 3: 12-23-1, 12-23-2, and 12-24-4 are channel samples and 1-10-1, 1-9-5, 12-23-3, 12-13-2, 12-14-4, and 12-26-1 are grab samples or samples from talus.

Mount Bastion (location 8). *Allen* [1962] reports on a single sample (Table 4) from a 1-m-thick coal bed at Mount Bastion. The analysis was reported on an air-dried basis, and we have recalculated it to an as-received basis for this report.

Willett Range (location 8). *Mulligan et al.* [1963b] collected 12 samples, three of which have ash contents greater than 50% and are not summarized in this study because they do not fit the definition of coal. Bed thicknesses are in parentheses. The nine coal samples used (Table 4) are as follows: channel samples 12-14-1 (0.6 m) and 12-14-2 (0.6 m) and grab samples 12-21-1 (0.7 m), 12-21-2 (0.2 m), 12-21-4 (0.9+ m), 12-21-5 (0.6 m), 12-21-7 (2.4 m), 12-21-9 (0.8 m), and 12-21-11 (2.3 m). In describing taking the grab samples, *Mulligan et al.* [1963b, p. 24] write that the beds "... were exposed in a cliff face. Channels could not be cut in these large hard beds in the time available so specimens had to be obtained by breaking representative fragments from the exposed faces." For interpretive purposes these samples can probably be treated as channel samples.

Mount Fleming (location 9). *Whitby et al.* [1983] collected two outcrop samples near a doleritic dike and reported on one (Table 5). A sample of a 1.6-m-thick bed, apparently a grab sample, was gravity separated as float 1.70 plus fines (the portion of the coal that floats in a fluid with specific gravity of 1.70).

Kennar Valley (location 10). Three coal beds were sampled by *Whitby et al.* [1983] (Table 5); beds 1, 3, and 6, from the uppermost bed down, are 0.9, 1.49, and 0.17 m thick, respectively (beds 2, 4, and 5 are rock). Within each coal bed, samples are numbered from the bottom up. Three analyses of bench samples from bed one,

TABLE 2. Proximate and Ultimate Analyses of Coal Samples From Freyberg Mountains and Allan Nunatak (Figure 2, Locations 2 and 6), As-Received Basis

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Freyberg Mountains [Dow and Neall, 1974]											
13/433	3.0	27.8	65.0	4.2					0.5	13,860	mvb
13/434	7.1	30.4	59.3	3.2					0.6	11,830	hvcB
Allan Nunatak [Gunn and Warren, 1962]											
MS 11 A	2.67	9.76	44.17	43.40					3.02	6,900	sa
MS 11 B	1.91	12.32	72.85	12.92					4.77	11,600	sa
Allan Nunatak [Schopf and Long, 1966]											
CGL-255	3.5	13.9	72.3	10.3	3.1	74.7	1.6	9.5	0.8	12,130	lvb
CGL-259	3.9	13.7	70.4	12.0	3.1	72.7	1.6	10.0	0.6	11,810	lvb

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; sa, semianthracite; lvb, low-volatile bituminous coal; mvb, medium-volatile bituminous coal; hvcB, high-volatile C bituminous coal. Analytical values not shown are not reported in source.

TABLE 3. Proximate and Ultimate Analyses of Coal Samples From Mount Gran (Figure 2, Location 7), As-Received Basis

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Schopf and Long [1966]											
Calkin-2	12.9	10.1	57.7	19.3	1.7	60.3	0.7	18.0	0.0	8,460	sa
Calkin-9c	7.9	10.1	82.7	4.1	2.3	82.6	1.0	9.5	0.5	12,740	an
Calkin-12b	9.0	5.3	77.1	8.6	2.4	76.8	1.1	10.8	0.3	11,790	an
Calkin-14	8.3	5.9	78.7	7.1	2.2	79.8	1.0	9.7	0.2	12,160	an
Mulligan et al. [1963a]											
12-23-1	14.9	5.4	66.6	13.1	2.7	67.1	0.4	16.4	0.3	10,110	an
1-10-1	6.2	6.2	75.0	12.6	2.4	74.5	0.8	9.3	0.4	11,620	an
1-9-5	1.2	4.7	84.4	9.7	0.5	85.5	0.0	4.2	0.1	11,950	an
12-23-3	1.5	4.4	76.1	18.0	0.6	76.7	0.0	4.7	0.0	10,590	an
12-23-2	14.1	4.5	71.6	9.8	2.6	72.6	0.6	14.2	0.2	10,890	an
12-24-4	7.8	10.9	66.8	14.5	2.5	68.9	0.9	12.1	1.1	10,600	sa
12-13-2	8.8	4.5	78.0	8.7	2.3	77.0	0.5	11.2	0.3	11,690	an
12-14-4	9.7	8.5	59.0	22.8	2.0	61.0	0.5	13.6	0.1	8,900	sa
12-26-1	4.2	5.6	83.1	7.1	1.1	83.8	0.2	7.6	0.2	12,050	an

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; an, anthracite; sa, semianthracite.

TABLE 4. Proximate and Ultimate Analyses of Coal Samples From Mount Bastion and Willett Range (Figure 2, Location 8), As-Received Basis

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Mount Bastion [Allen, 1962]											
AG 1965	9.7	7.6	53.3	29.4					0.2	8,260	sa
Willett Range [Mulligan et al., 1963b]											
12-21-1	8.1	8.7	72.4	10.8	2.1	73.4	0.8	12.6	0.3	11,040	sa
12-21-2	6.8	8.6	76.0	8.6	2.3	77.5	0.8	10.4	0.4	11,920	sa
12-21-4	7.7	21.4	57.5	13.4	2.1	71.2	0.8	12.2	0.3	10,820	mvb
12-21-5	3.7	11.0	73.2	12.1	6.2	75.6	1.2	7.9	0.6	12,040	sa
12-21-7	3.6	12.2	66.5	17.7	2.6	69.1	1.2	8.8	0.6	11,100	sa
12-21-9	3.8	12.3	61.8	22.1	2.4	64.4	1.1	9.3	0.7	10,290	lvb
12-21-11	5.6	11.3	72.9	10.2	2.5	74.8	1.2	10.4	0.9	11,830	sa
12-14-2	12.2	11.0	40.3	36.5	2.0	44.1	0.2	16.9	0.3	6,320	lvb
12-14-1	13.5	13.2	53.1	20.2	2.2	57.5	0.3	19.6	0.2	8,240	lvb

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; sa, semianthracite; lvb, low-volatile bituminous coal; mvb, medium-volatile bituminous coal. Analytical values not shown are not reported in source.

TABLE 5. Proximate and Ultimate Analyses of Coal Samples From Mount Fleming, Kennar Valley, and Mount Crean (Figure 2, Locations 9, 10, and 11), As-Received Basis Except As Noted In Text

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Mount Fleming [Whitby et al., 1983]											
T2-T6	7.9	12.2	70.5	17.3					1.01		an
Kennar Valley [Whitby et al., 1983]											
1/4	6.1	8.8	73.2	11.9					0.63		sa
1/3	6.0	8.8	69.8	15.4					0.64		sa
1/2	6.2	9.4	68.7	15.7					0.65		sa
3/2	4.5	10.4	76.6	8.5					0.72		sa
6/2	7.2	11.8	78.3	9.9					0.74		an
Mount Crean (From Kyle [1976], Quoted by Rose and McElroy [1987])											
23447	4.8	10.1	77.4	7.7					0.94	12,440	sa
23475	6.0	12.0	76.4	5.6					0.72	12,330	sa

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; an, anthracite; sa, semianthracite. Analytical values not shown are not reported in source.

samples 1/4, 1/3, and 1/2, are raw coal. Bench samples 3/2 and 6/2, from beds 3 and 6, are gravity separates as float 1.70 plus fines. Bench samples 1/1 and 3/1 were not reported separately, but 1/1 is included in a composite of seam 1 as float 1.70 plus fines, and 3/1 is included in a composite with seam 1 as float 1.70 plus fines.

Mount Crean (location 11). Analyses of two coal samples (Table 5) from the Weller Coal Measures are taken from Kyle [1976] as quoted by Rose and McElroy [1987]. Sampling methods and laboratory procedures are not described.

Nimrod-Ohio Basin

Moore Mountains (location 15). Barrett [1969] reports on one coal sample (Table 6) from a 1-m-thick bed in the Moore Mountains. The method of sampling is not described. The sample was gravity separated as float 1.60.

Cranfield Peak (location 16). Barrett [1969] reports on one coal sample (Table 6) from a bed of unspecified thickness at Cranfield Peak. The method of sampling is not described. The sample was gravity separated as float 1.60.

Mount Ropar (location 18). Barrett [1969] reports on two coal samples (Table 7) from Mount Ropar. The method of sampling is not described, and thicknesses of

coal beds and whether samples are from different beds are not reported. The samples were gravity separated as float 1.60.

Law Glacier (location 18). Schopf and Long [1966] report analysis (Table 7) of a single sample with ash content less than 20%, which was collected by G. W. Grindley. Method of sampling and thickness of coal bed are not reported.

Dominion Range (location 22). Schopf and Long [1966] report analyses (Table 7) of two samples with ash contents of 20% or less. These samples were collected by V. R. McGregor. Method of sampling and thickness of coal bed(s) are not reported.

Graphite Peak (location 24). Barrett [1969] reports an analysis of one coal sample from the Buckley Formation at Graphite Peak. Method of sampling and thickness of coal bed are not reported. The sample was gravity separated as float 1.60.

Nilsen Plateau ("Thorvald Nilsen Mountains") (location 28). Schopf and Long [1966] report the analyses (Table 7) of four samples with ash contents of 20% or less. These samples were collected by W. E. Long, apparently from different beds. Method of sampling and thickness of coal beds are not reported.

Mount Weaver (location 29). Schopf and Long [1966]

TABLE 6. Proximate and Ultimate Analyses of Coal Samples From Moore Mountains, Cranfield Peak, and Mount Ropar (Figure 2, Locations 15, 16, and 18), As-Received Basis [Barrett, 1969]

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Moore Mountains											
A321	2.9	14.8	74.4	8.1	2.7	77.0	1.9	9.8	0.5	12,250	lvb
Cranfield Peak											
C203	3.5	12.2	77.4	6.9	2.9	78.1	1.9	9.4	0.8	12,600	sa
Mount Ropar											
R005	3.6	14.2	74.4	7.8	2.5	75.6	1.9	11.5	0.7	12,010	lvb
R008	2.8	12.1	74.4	10.6	2.7	74.9	1.9	8.9	1.0	11,970	sa

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; sa, semianthracite; lvb, low-volatile bituminous coal.

TABLE 7. Proximate and Ultimate Analyses of Coal Samples From Law Glacier, Dominion Range, Graphite Peak, and Thorvald Nilsen Mountains (Figure 2, Locations 18, 22, 24, and 28), As-Received Basis

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Law Glacier [Schopf and Long, 1966]											
CS-10471	3.9	12.8	68.0	15.3					0.5	11,340	lvb
Dominion Range [Schopf and Long, 1966]											
116	6.5	16.2	61.1	16.2					0.5	10,390	lvb
117	1.5	3.3	76.6	18.6					0.1	11,670	an
Graphite Peak [Barrett, 1969]											
G012	7.9	23.1	47.6	21.4	2.0	52.7	1.2	22.3	0.4	7,430	mvb
Thorvald Nilsen Mountains [Schopf and Long, 1966]											
CGL-251	4.6	18.2	66.4	10.8	3.0	69.4	1.9	14.2	0.7	11,100	lvb
CGL-252	3.4	13.4	76.7	6.5	2.7	77.6	2.0	10.6	0.6	12,330	lvb
CGL-253	3.3	15.6	71.2	9.9	2.9	73.8	1.6	11.3	0.5	11,810	lvb
CGL-254	4.3	18.8	68.4	8.5	3.0	72.0	1.7	14.2	0.6	11,440	lvb

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; an, anthracite; lvb, low-volatile bituminous coal; mvb, medium-volatile bituminous coal. Analytical values not shown are not reported in source.

report proximate analyses of 30 coal samples with ash content of 20% or less (Table 8). Twenty-six samples were collected by V. H. Minshew, and four samples are from Blackburn [1937], reprinted in the work of Schopf and Long [1966]. Method of sampling and thickness of coal beds are not reported. Ultimate analyses were done on 13 of the above samples.

Mount Glossopteris (location 31). Long [1964b] and Schopf and Long [1966] report proximate analyses of 23 coal samples (Table 9). Twenty of the samples analyzed are float 1.59 according to Schopf and Long [1966]. The other three samples we assume to be nonfloat. Ultimate analyses were reported for five samples. Method of sampling and thickness of coal beds are not reported.

Canyon Peak (location 32). Long [1964b] reports proximate analyses of five coal samples (Table 10). All of the samples were collected by W. E. Long. All samples are

float 1.59. Method of sampling and thickness of coal beds are not reported.

Mount Schopf (location 32). Long [1964b] measured three stratigraphic sections on the flanks of Mount Schopf that contain coal in the Mount Glossopteris Formation. Section 13 is on Terrace Ridge, which juts northwestward from the west end of the mountain; section 14 is on the next ridge 1.5 km to the east; and section 15 is on the northeast ridge of the mountain, some 6 km farther to the east. Forty-two analyses of coal collected from these measured sections are listed in Table 10. The method of sampling is not reported for the samples of the measured sections. For 11 of the samples the analysis was of a float sample obtained at variously 1.59, 1.70, or 1.75 specific gravity [Schopf and Long, 1966].

On Terrace Ridge (section 13), Long excavated into a

TABLE 8. Proximate and Ultimate Analyses of Coal Samples From Mount Weaver (Figure 2, Location 29), As-Received Basis [*Schopf and Long, 1966*]

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
CGL-197	2.6	15.2	73.3	8.9					0.7	12,200	lvb
CGL-198	2.6	20.1	68.0	9.3	3.0	75.6	1.9	9.5	0.7	12,250	lvb
CGL-200	2.7	12.9	73.5	10.9	2.9	74.4	1.9	9.3	0.6	12,090	sa
CGL-203	2.6	13.5	68.2	15.7	2.6	69.4	1.7	9.9	0.7	11,240	lvb
CGL-209	3.2	12.4	73.0	11.4	2.4	73.6	1.7	10.1	0.8	11,600	sa
CGL-212	3.2	16.6	67.7	12.5					0.6	11,340	lvb
CGL-213	2.9	17.4	69.9	9.8	3.1	72.5	1.7	12.2	0.7	11,740	lvb
CGL-215	3.4	19.8	67.6	9.2					0.7	11,570	lvb
CGL-216	2.8	17.8	71.4	8.0	3.2	75.3	1.4	11.6	0.5	12,210	lvb
CGL-219	2.9	17.5	70.0	9.6	3.1	73.5	1.5	11.8	0.5	11,900	lvb
CGL-222	2.2	14.1	63.7	20.0					0.7	10,750	lvb
CGL-223	2.5	15.2	68.3	14.0	3.0	70.4	1.7	10.3	0.6	11,500	lvb
CGL-224	2.9	18.4	72.8	5.9					0.7	12,320	lvb
CGL-225	2.8	17.0	64.1	16.1					0.6	10,980	lvb
CGL-226	2.6	17.4	72.9	7.1					0.6	12,280	lvb
CGL-228	2.8	17.7	70.2	9.3	3.2	73.3	2.0	11.6	0.6	11,990	lvb
CGL-229	3.0	18.6	74.5	3.9					0.6	12,670	lvb
CGL-231	2.5	15.9	74.2	7.4					0.5	12,450	lvb
CGL-233	2.3	15.5	73.1	9.1	3.2	75.6	2.0	9.5	0.6	12,310	lvb
CGL-235	2.6	14.7	65.0	17.7					0.6	10,860	lvb
CGL-237	2.8	14.4	76.1	6.7					0.6	12,680	lvb
CGL-240	2.7	13.6	66.2	17.5					0.6	10,810	lvb
CGL-243	3.1	13.8	63.6	19.5					0.6	10,460	lvb
CGL-246	2.9	11.9	66.5	18.7	2.1	67.4	1.5	9.7	0.6	10,600	sa
CGL-249	1.7	4.4	78.8	15.1	0.6	77.5	0.1	6.6	0.1	11,150	an
CGL-248	0.9	3.5	80.2	15.4	0.5	79.7	0.1	4.2	0.1	11,350	an
CGL-193	2.3	10.0	74.9	12.8					0.7	12,020	sa
CGL-190	2.8	16.8	73.5	6.9					0.6	12,270	lvb
CGL-181	2.1	11.2	69.5	17.2					0.6	11,370	sa
CGL-180	3.1	15.4	65.8	15.7					0.7	10,890	lvb

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; an, anthracite; sa, semianthracite; lvb, low-volatile bituminous coal. Analytical values not shown are not reported in source.

TABLE 9. Proximate and Ultimate Analyses of Coal Samples From Mount Glossopteris (Figure 2, Location 31), As-Received Basis

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Mount Glossopteris, Section 16 [Long, 1964b]											
CGL 156 F	6.0	14.7	67.7	11.6					0.6	11,110	lvb
CGL 157 F	5.5	18.2	66.4	9.9					0.6	11,440	lvb
CGL 158 F	5.6	15.0	69.9	9.5					0.6	11,430	lvb
CGL 159 F	5.6	14.3	72.7	7.4	2.9	74.6	1.5	13.0	0.6	11,810	lvb
CGL 160 F	5.4	12.7	73.7	8.2					0.6	11,980	sa
CGL 162 F	7.9	14.7	67.2	10.2	2.4	70.2	1.0	15.9	0.3	10,620	lvb
Mount Glossopteris, Section 17 [Long, 1964b]											
CGL 107	2.7	7.0	49.5	40.8	2.1	49.7	0.9	6.0	0.5	8,140	an
CGL 106	2.6	7.1	44.8	45.5	2.0	45.9	0.9	5.3	0.4	7,460	an
CGL 138 F	3.2	9.6	71.8	15.4					0.7	11,850	sa
CGL 139 F	3.2	8.2	68.7	19.9					0.5	11,250	sa
CGL 140 F	4.8	12.1	74.7	8.4					0.7	12,160	sa
CGL 141 F	5.2	12.7	74.6	7.5					0.7	12,110	sa
CGL 142 F	5.0	12.1	76.7	6.2					0.7	12,430	sa
CGL 143 F	5.5	13.5	72.8	8.2					0.6	11,730	lvb
CGL 144 F	5.9	13.3	72.8	8.0					0.6	11,720	lvb
CGL 145 F	4.6	11.3	79.3	4.8					0.5	12,710	sa
CGL 147 F	4.4	10.7	75.2	9.7					0.7	12,300	sa
CGL 148 F	3.8	9.5	76.7	10.0					0.7	12,510	sa
CGL 150 F	3.9	8.6	78.9	8.6	3.0	78.7	1.5	7.6	0.6	12,770	sa
CGL 151 F	3.7	9.2	79.5	7.6					0.6	12,970	sa
Mount Glossopteris [Schopf and Long, 1966]											
CGL-51	3.2	10.4	74.6	11.8	3.0	75.4	1.3	7.8	0.7	12,290	sa
CGL-126 F	3.3	9.7	73.4	13.6	3.0	73.9	1.4	7.4	0.7	12,150	sa
CGL-153 F	8.0	14.9	75.3	1.8					0.4	12,000	lvb

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; an, anthracite; sa, semianthracite; lvb, low-volatile bituminous coal. Analytical data not shown are not reported in source.

TABLE 10. Proximate and Ultimate Analyses of Coal Samples From Mount Schopf and Canyon Peak (Figure 2, Location 32), As-Received Basis

Sample No.	Proximate Analysis				Ultimate Analysis					Other Properties	
	Moisture, %	Volatile Matter, %	Fixed Carbon, %	Ash, %	H, %	C, %	N, %	O, %	S, %	Heat of Combustion, Btu/lb	Apparent Rank (ASTM)
Canyon Peak, Section 4 [Long, 1964b]											
CGL 119 F	4.1	11.7	74.8	9.4					0.7	12,590	sa
CGL 120 F	4.1	10.8	70.3	14.8					0.6	11,630	sa
CGL 122 F	3.5	10.4	70.8	15.3					0.6	11,760	sa
CGL 123 F	3.9	10.1	72.7	13.3					0.7	12,020	sa
CGL 125 F	3.6	10.2	73.3	12.9					0.7	12,170	sa
Terrace Ridge on Mount Schopf, Section 13 [Long, 1964b]											
CGL 82	7.0	12.8	51.0	29.2	2.0	54.2	1.3	13.0	0.3	8,170	lvb
CGL 83	8.0	14.3	67.5	10.2	2.6	70.5	1.4	14.9	0.4	10,860	lvb
CGL 87	5.7	12.7	43.7	37.9	2.0	46.5	1.3	11.8	0.5	7,150	lvb
CGL 88	4.9	11.3	50.0	33.8	2.2	51.6	1.4	10.6	0.4	8,070	lvb
CGL 100	5.5	13.2	58.5	22.8	2.3	60.4	1.6	12.4	0.5	9,500	lvb
CGL 89	5.8	13.6	59.9	20.7	2.5	61.8	1.5	13.0	0.5	9,690	lvb
CGL 90	5.4	12.0	45.0	37.6							lvb
CGL 91	5.3	13.0	42.3	39.4	2.1	46.1	1.2	10.9	0.3	7,140	lvb
CGL 92	6.1	14.5	61.1	18.3	2.5	63.9	1.4	13.4	0.5	10,000	lvb
CGL 105	7.6	11.9	68.2	12.3	2.6	70.5	1.8	12.4	0.4	10,990	sa
CGL 164 F	7.3	15.3	71.7	5.7					0.5	11,580	lvb
CGL 76	4.1	10.5	37.2	48.2	1.7	40.0	1.1	8.3	0.7	6,230	lvb
CGL 75	4.8	12.0	51.7	31.5	2.2	54.1	1.4	10.4	0.4	8,440	lvb
CGL 74	4.0	10.0	38.9	47.1	1.8	41.2	1.2	8.4	0.3	6,400	sa
Terrace Ridge on Mount Schopf [Schapiro and Gray, 1966]											
95	2.7	6.5	45.6	47.9	1.7	46.4	1.2	2.4	0.4		ma
98	5.4	11.9	52.6	35.5							an
Dirty Diamond Adit, Terrace Ridge on Mount Schopf [Long, 1964b]											
CGL 118	6.7	15.1	54.5	23.7	2.6	58.0	1.1	14.2	0.4	9,050	lvb
CGL 117	6.5	15.0	62.6	15.9	2.7	65.3	1.1	14.5	0.5	10,260	lvb
CGL 116	6.7	15.9	56.6	20.8	2.6	60.6	1.1	14.4	0.5	9,490	lvb
CGL 115	7.9	17.6	65.9	8.6	2.9	69.5	1.3	17.2	0.5	10,810	lvb
CGL 114	7.5	17.3	63.1	12.1	3.0	65.9	1.4	17.0	0.6	10,350	lvb
CGL 113	5.4	12.4	41.1	41.1	2.1	43.3	0.9	12.3	0.3	6,750	lvb
CGL 112	6.7	14.7	50.4	28.1	2.4	53.8	1.1	14.2	0.4	8,370	lvb
CGL 111	6.2	14.2	47.6	32.0	2.4	50.1	1.1	14.0	0.4	7,870	lvb
CGL 110	6.0	13.4	43.2	37.4	2.4	45.1	1.0	13.7	0.4	7,130	lvb
CGL 109	6.6	15.1	54.7	23.6	2.6	57.8	1.6	13.9	0.5	9,000	lvb
CGL 108	7.4	17.4	61.6	13.6	2.8	65.4	1.7	16.0	0.5	10,230	lvb
Mount Schopf, Section 14 [Long, 1964b]											
CGL 128	6.9	15.0	72.1	6.0					0.6	11,700	lvb
CGL 129	6.9	15.8	73.1	4.2					0.6	11,760	lvb
CGL 130	6.4	14.1	78.3	1.2					0.5	12,430	lvb
CGL 131	7.2	14.9	61.9	16.0					0.4	10,130	lvb
Mount Schopf, Section 15 [Long, 1964b]											
CGL 132	4.1	11.2	76.2	8.5	3.2	77.5	1.5	8.6	0.7	12,660	sa
CGL 133	6.5	28.6	59.0	5.9					0.7	11,720	hvCb
CGL 134	7.7	17.5	71.0	3.8	2.9	74.4	1.4	17.0	0.5	11,520	lvb
CGL 135	7.2	16.0	72.1	4.7					0.5	11,590	lvb
CGL 136	6.8	14.9	58.6	19.7					0.3	9,270	lvb
CGL 37	0.8	2.4	64.9	31.9							ma

Abbreviations: H, hydrogen; C, carbon; N, nitrogen; O, oxygen; S, sulfur; ma, meta-anthracite; an, anthracite; sa, semianthracite; lvb, low-volatile bituminous coal; hvCb, high-volatile C bituminous coal. Analytical values not shown are not reported in source. Ranks calculated for samples CGL 90, CGL 98, and CGL 37 by assuming 0.5% sulfur content.

3.6-m coal bed in what he called the Dirty Diamond Adit in order to obtain coal samples fresher than material exposed at the surface. Eleven of the samples listed in Table 10 are coal collected from the bed exposed in the adit. Ten of these are bench channel samples of intervals of differing thickness, and one (CGL-118) is a composite representing the whole bed. So far as we can determine, none of the 11 samples was subjected to float-sink treatment.

DISCUSSION OF COAL QUALITY

Coal is defined as a "... readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material, formed from compaction or induration of variously altered plant remains similar to those of peaty deposits" [Schopf, 1956]. Coal can be classified by rank, grade, and type.

Classification by rank places the coal according to the degree of coalification, or progressive alteration, in the series from lignite to anthracite. One of the commonly employed systems for rank classification is the "Standard classification of coals by rank" (D388-84) adopted by the American Society for Testing and Materials [American Society for Testing and Materials, 1986, pp. 247-252]. In this system, coals of lower rank are classified according to moist, mineral-matter-free heat of combustion in British thermal units per pound supplemented by information about the agglomerating characteristics of the coal. Higher rank coals are classified according to dry, mineral-matter-free fixed carbon percentage. Both are calculated by Parr formulas.

The ASTM standard states, "A standard rank determination cannot be made unless samples have been obtained in accordance with Section 7.1" [American Society for Testing and Materials, 1986, p. 249]. Section 7.1.2 [American Society for Testing and Materials, 1986, p. 248] states, "Analyses of samples from outcrops or from weathered or oxidized coal shall not be used for classification by rank." However, the ASTM standard does define a comparative rank indicator designated "apparent rank" for samples taken under unspecified conditions [American Society for Testing and Materials, 1986, p. 249]. Apparent rank designations can "... indicate a correct relative position for the coal sample analyzed but do not imply any standards of bed sampling" [American Society for Testing and Materials, 1986, p. 249]. All rank designations discussed in this report are apparent rank.

Any coal sample collected from an outcrop is assumed to be weathered [Hatch and Affolter, 1981]. In discussing analyses of samples from the Mount Glossopteris Formation on Terrace Ridge, Schopf and Long [1966] note that samples collected from the outcrop and samples collected from the same bed in an adit 3.5 m below the surface show little difference in chemical and

physical properties. Affolter and Stricker [1987], and work in progress by G. D. Stricker on coals from the North Slope of Alaska, also suggest that permafrost has a mitigating effect on weathering and that exposed coals may not weather and oxidize much deeper than a few centimeters. Their studies show that chemical and physical properties of channel samples of coal from outcrops are essentially the same as the properties of unweathered samples of the same beds that were collected from cores or deep adits. In the case of coal samples collected from outcrops under permafrost conditions, as in Antarctica, the apparent rank of coals may be a near approximation of the actual rank.

Classification of coals by grade is based on the amount of deleterious constituents in the coal. The deleterious constituents are those, such as ash and sulfur, that affect the utilization potential of coals or the environmental impact of usage. Any characteristic or property of a coal may be considered deleterious if it adversely affects a particular use of the coal. For example, the properties that make a coal desirable for making blast furnace coke for the steel industry may be undesirable if the use anticipated is conventional powdered-coal combustion technology to generate electricity.

Classification of coals by type is based upon distinctions among the original materials that accumulated to eventually become coal. Schapiro and Gray [1966], Mackowsky [1975], and Whitby et al. [1983] have done initial studies of coal types in the Transantarctic Mountains. Both megascopic and microscopic studies suggest that many of the Antarctic coals contain less vitrinite, the constituent that originated as the woody parts of plants, than most coals of late Paleozoic age from the northern hemisphere. Similarly, the Antarctic coals generally seem to contain more silt and clay-sized material disseminated through the coal than is common in northern hemisphere coals. Both of these factors require further study, as they can affect ways in which a coal can be used.

In addition, the ASTM rank classification [American Society for Testing and Materials, 1986, D388-84, Section 1, p. 247] states, "The precision of the classification of impure coal may be impaired by the effect of large amounts of mineral matter on the determination of volatile matter and calorific value, and on their calculation to the mineral-matter-free basis." According to ASTM standards, fixed carbon can be used for rank designation in place of volatile matter. Problem coals "... contain only a small amount of vitrain and commonly consist mainly of dull attrital (finely divided-authors) materials." For this reason, type classification is important to understanding the constitution and properties of high-ash coals.

Biases may be introduced by different sampling methods and by different analytical techniques used in dif-

ferent laboratories through the years. Nonetheless, the analyses of coals of Permian age from the Transantarctic Mountains are sufficiently consistent to permit certain generalizations. The apparent rank of the 144 samples of Permian coals ranges from high-volatile C bituminous coal to meta-anthracite. A majority of the samples have an apparent rank of low-volatile bituminous coal (74) and semianthracite (45). Eighteen samples have an apparent rank of anthracite, three samples have an apparent rank of medium-volatile bituminous coal, and two high-ash samples have apparent ranks of meta-anthracite. Two samples have an apparent rank of high-volatile C bituminous coal, a surprisingly low rank for coal in the Transantarctic Mountains. A detailed exploration and sampling program might find more low-rank coals.

The literature indicates that several workers have washed coal samples or used float-sink methods to reduce ash content before performing proximate and ultimate analyses [see *Whitby et al.*, 1983; *Barrett*, 1969; *Schopf and Long*, 1966]. *Schopf and Long* [1966] did not report proximate or ultimate analyses of any coal that contained more than 20% ash, nor did they indicate what proportion of their samples contained more than 20% ash. Both these procedures can bias the published data to suggest that the Antarctic coals have lower ash content than would be indicated had raw coal samples been analyzed and analyses of all samples been reported. In addition, as was mentioned earlier, rank classification of some types of high-ash coal may be imprecise. It is possible that some of the application of float-sink methods was done in an attempt to evade the potential problem of imprecision in rank designation.

The coal samples described in this report were not all collected, handled, and analyzed with standard methods that allow meaningful, detailed comparison of the analytical and testing results of the whole suite of samples. Twenty-nine samples of the total 144 reported earlier (Tables 2 through 10) were selected as apparently representative of the range of composition of the Antarctic coals. All of the 29 apparently represent attempts to collect representative samples of coal beds through their total thickness, or at least the part of a bed accessible, either by sampling the whole bed at once or sampling by benches. So far as can be determined, none of these samples were subjected to float-sink treatment.

Tables 11, 12, and 13 present the analytical results, or statistical summary of analytical results, for these 29 samples, divided into three groups.

Group 1 (Table 11) is composed of seven samples collected from four separate locations by four different individuals or field parties. The group exhibits a wide range in properties. Despite the possible lack of comparability owing to the diversity of sampling localities and techniques used in collecting, storing, and analyzing the coal, most of the differences in properties are so large

that they probably are real. The coals collected by *Dow and Neall* [1974] in northern Victoria Land are low in ash (less than 8%) and low in sulfur (1% or less) and have heat values greater than the mean for the group. One of the samples has an apparent rank of high-volatile C bituminous coal, lower in rank than any other sample in Tables 11, 12, or 13, and the other sample has an apparent rank of medium-volatile bituminous coal, which is matched by only two other samples of the total 144 whose analyses are listed in this report. The two Allan Hills samples (Table 11) have high sulfur contents (3% or more). All but one of the other samples summarized in Tables 11, 12, and 13 are classed as low sulfur; one is in the low end of the medium sulfur range. Depending on the characteristics used for classification, there are at least three different apparent ranks and grades of coals represented by the samples in group 1. The samples in this group illustrate the fact that much remains to be learned about the distribution of ranks and grades of coals present in different parts of the Transantarctic Mountains.

Group 2 comprises 12 samples from two locations in the South Victoria Basin. The samples were collected by essentially the same individuals and were presumably collected, handled, and analyzed similarly. The statistical summaries of the two suites of sample analyses (Table 12) show that comparable samples collected from coal beds in close proximity can exhibit a fairly wide range in some properties. For examples, the sample suite from the Willett Range has a fairly wide range in ash content and the sample suite from Mount Gran shows a wide range in sulfur content. However, the arithmetic means are probably reasonably representative of the samples from the two areas and show that the average coal of the Mount Gran area is anthracite and the average coal of the Willett Range is of low-volatile bituminous rank. The sample suites from both areas are of low sulfur content. The Mount Gran sample suite shows a mean ash content near the middle of the medium ash class, and the Willett Range sample suite has a mean ash content in the lowest part of the high ash class. The few published type descriptions of these coals indicate a range from preponderantly fine- to medium-banded bright coal to sparsely thin-banded, highly attrital coal with a moderately dull luster [*Mulligan et al.*, 1963a, b].

Group 3 is composed of 10 samples collected from the Dirty Diamond Adit. Table 13 presents weighted means and ranges of analytical values. These analyses provide the best data available on the physical and chemical characteristics of an Antarctic Permian coal bed. The sample analyses are listed individually in Table 10; the stratigraphic sequence of the sampled and nonsampled parts (benches) of the coal bed is shown in Figure 5. Although it is not stated explicitly by *Long* [1964b], we assume that the parts of the coal bed that were not

TABLE 11.
Analytical Data In
Group 1, Seven
Coal Samples
From Four Areas
In North and
South Victoria
Basins

	Moisture, %	Ash, %	Volatile Matter, %	Fixed Carbon, %	Sulfur, %	Btu/lb	Apparent Rank (ASTM)
Freyberg Mountains (Location 2, Figure 2), North Victoria Basin; Dow and Neall [1974]							
Sample 13/433	3.0	4.2	27.8	65.0	0.5	13,860	mvb
Sample 13/434	7.1	3.2	30.4	59.3	0.6	11,830	lvCb
Allan Nunatak (Location 6, Figure 2), South Victoria Basin; Gunn and Warren [1962]							
Sample MS-11A	2.7	43.4	9.8	44.2	3.0	6,900	sa
Sample MS-11B	1.9	12.9	12.3	72.9	4.8	11,600	sa
Mount Bastion (Location 8, Figure 2), South Victoria Basin; Allen [1962]							
Sample AG 1965	9.7	29.4	7.6	53.3	0.2	8,260	sa
Mount Crean (Location 11, Figure 2), South Victoria Basin; Kyle [1976] cited by Rose and McElroy [1987]							
Sample 23447	4.8	7.7	10.1	77.4	0.9	12,440	sa
Sample 23475	6.0	5.6	12.0	76.4	0.7	12,330	sa

TABLE 12.
Statistical
Summary of
Analytical Data In
Group 2, Twelve
Coal Samples
From Mount Gran
and the Willett
Range

Mount Gran (Location 7, Figure 2), South Victoria Basin; Mulligan et al. [1963a]. Summary of analyses of sample numbers 12-32-1, 12-23-2, and 12-24-4. Individual analyses shown in Table 3.							
Mean	12.3	12.5	6.9	68.3	0.5	10,530	an
Arithmetic deviation	3.9	2.4	3.5	2.8	0.5	390	
Range: minimum	7.8	9.8	4.5	66.6	0.1	10,110	
Range: maximum	14.9	14.5	10.9	71.6	1.1	10,890	
Willett Range (Location 8, Figure 2), South Victoria Basin; Mulligan et al. [1963b]. Summary of nine analyses. Individual analyses shown in Table 4.							
Mean	7.2	16.8	12.2	63.7	0.5	10,400	lvb
Arithmetic deviation	3.6	8.7	3.8	11.8	0.2	1,920	
Range: minimum	3.6	8.6	8.6	40.3	0.2	6,320	
Range: maximum	13.5	36.5	21.4	76.0	0.9	12,040	

TABLE 13.
Weighted Means
and Ranges of
Analytical Data in
Group 3, Ten Coal
Samples

Dirty Diamond Mine in Terrace Ridge on Mount Schopf in the Ohio Range, Nimrod-Ohio Basin (Location 31, Figure 2) (Sample Numbers CGL 108, CGL 109, CGL 110, CGL 111, CGL 112, CGL 113, CGL 114, CGL 115, CGL 116, CGL 117 [Long, 1964b]; individual analyses shown in Table 10)							
Weighted mean	6.7	23.1	15.4	54.7	0.5	9,030	lvb
Range: minimum	5.4	8.6	12.4	41.1	0.3	6,750	
Range: maximum	7.9	41.1	17.6	65.9	0.6	10,810	

Abbreviations: an, anthracite; sa, semianthracite; mvb, medium-volatile bituminous coal; hvCb, high-volatile C bituminous coal; lvb, low-volatile bituminous coal.

sampled were rejected as impure coal or noncoal (more than 50% ash) on the basis of megascopic examination as samples were collected.

Analysis of a composite sample (CGL-118) that was collected to represent the coal bed in the adit is shown in Table 10. The analytical values for this sample are very similar to the weighted means derived for the 10 Dirty Diamond Adit bench samples (Table 13). However, this similarity cannot be evaluated because sampling methods and procedures were not described.

As is shown in Figure 5, the 10 bench channel samples are separated by nine parts of the coal bed that were not sampled. In the description by Long [1964b], a nonsampled unit about 1 inch thick is present at the top of the bed; this unit is not included in Figure 5. The weighted mean of the 10 bench samples represents a coal of low-volatile bituminous rank with a dry, mineral-matter-free fixed carbon content of about 80% and a moist,

mineral-matter-free heat of combustion of about 12,000 Btu/lb. The coal would be characterized as of low sulfur content (1% or less) and high ash content (more than 15%). Presumably, a channel sample of the whole bed would have a greater ash content if the nonsampled parts of the whole coal bed are more impure than the sampled parts.

Tables 11, 12, and 13 show the following: (1) the Permian coals in different parts of the Transantarctic Mountains are of considerably different apparent ranks and grades, (2) coals of similar apparent rank from different coal beds in relatively small areas can display a wide range in grade characteristics, (3) a sample suite from an individual coal bed displays a fairly wide range in grade characteristics, and (4) much remains to be learned about the range in quality characteristics and the reasons therefore of the coals of the Transantarctic Mountains.

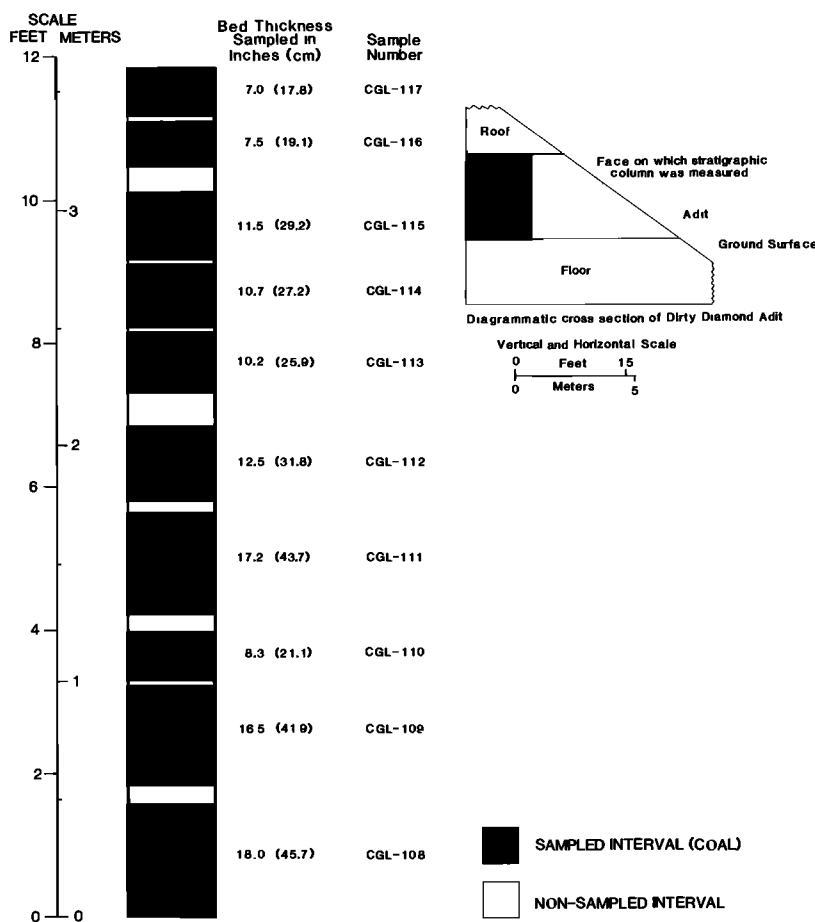


Fig. 5. Diagrammatic cross section of the Dirty Diamond Mine in Terrace Ridge on Mount Schopf (modified from Long [1964b]) and stratigraphic column of coal bed measured at the back of the adit (constructed from data of Long [1964b]).

RESOURCES OF COAL				
AREA: (MINE, DISTRICT, FIELD, STATE, ETC.)			UNITS: (SHORT TONS)	
CUMULATIVE PRODUCTION	IDENTIFIED RESOURCES		UNDISCOVERED RESOURCES	
	DEMONSTRATED		PROBABILITY RANGE	
	MEASURED	INDICATED	INFERRED	(or)
				HYPOTHETICAL
ECONOMIC	RESERVES		+	
MARGINALLY ECONOMIC	MARGINAL RESERVES		+	
SUBECONOMIC	SUBECONOMIC RESOURCES		+	
OTHER OCCURRENCES	INCLUDES	NONCONVENTIONAL	MATERIALS	

BY: (AUTHOR)

DATE:

A PORTION OF RESERVES OR ANY RESOURCE CATEGORY MAY BE RESTRICTED FROM EXTRACTION BY LAWS OR REGULATIONS.

Fig. 6. Format and classification of coal resources by reserves and subeconomic resources categories [from Wood *et al.*, 1983].

The following conclusions regarding the status of coal quality studies in the Transantarctic Mountains seem warranted by the results of this study:

1. The available sample descriptions are not adequate to form the basis of a modern detailed data base. Descriptions are lacking for many samples and outcrops, and with some excellent exceptions, quality of information suffers from lack of uniformity.

2. The existing coal quality data base suffers from a great lack of information about the philosophy, methodology, and technology used. The procedures of collecting, packing, transporting, and laboratory handling and analysis are reported in only a few cases.

3. Many of the chemical and physical determinations derived by analytical testing, particularly older information, do not meet modern requirements for coal evaluation. Proximate analysis data are commonly incomplete and/or have been biased in some manner. Usable ultimate analysis data are very scanty and essentially confined to coal suites from small areas. Major-, minor-, and trace-element data are almost completely lacking.

4. Information about type classification is inadequate and, with a few exceptions, may not be comparable with the results of current research methods and philosophy.

In order to be able to answer future questions on coal quality in the Transantarctic Mountains, we suggest that a program be designed specifically for the collection of coal samples and associated rocks by standard and carefully documented techniques and the acquisition of

chemical and physical data by standardized, internationally accepted methods and procedures. Such a program should include these guidelines:

1. Develop a program to collect representative samples of overburden, coal, and underburden in order to provide data that will further understanding of the geologic history of the coal-bearing rock sequences in the Permian basins in the Transantarctic Mountains.

2. Perform standard comprehensive chemical, physical, mineralogical, and petrologic analyses of samples to determine coal quality factors and relate these results to the stratigraphic and depositional framework of the coal-bearing rocks and the coals therein; from these data, develop geochemical models for predicting and evaluating coal quality, geochemical trends, and utilization potential.

ESTIMATES OF COAL RESOURCES

Methodology

The U.S. Geological Survey (USGS) coal resource classification [Wood *et al.*, 1983] is a system that divides coal resources into categories depending upon the degree of geologic assurance that they exist. With increasing distance from a point of information, an outcrop, drill hole, or trench, the geologic assurance decreases. This resource classification system is summarized in Figure 6.

Identified coal resources have sufficient geological assurances that the location, rank, quality, and quantity are known from outcrops, trenches, or drill holes. By convention this assurance extends to a distance of 4.8 km (3 mi) from an outcrop, trench, or drill hole.

Hypothetical coal resources have low geologic assurances and no outcrop, trench, or drill hole information to confirm that coal is present. The resource calculations are based on the premise that coal is probably present because analogous geologic conditions extend beyond the 4.8-km limit of identified resources.

This resource classification system, explained in detail in U.S. Geological Survey Circular 891 [Wood *et al.*, 1983], is designed to be applied to individual coal beds. In addition, it is designed for regions where density of information is greater than it is in the Transantarctic Mountains. In the Transantarctic Mountains, individual coal beds have not been correlated between even the closer outcrops in many cases; in many parts of the region outcrops are tens of kilometers apart, and the intervening country lies beneath ice and snow. In addition, the commonly observed thinning and pinching out of coal beds over short distances suggest that most coal beds have limited lateral extent. Therefore in this study we have not assumed lateral continuity of individual beds. Instead, we have assumed that the total quantity of coal in the coal-bearing portion of the sedimentary section varies more or less systematically through the region and based our estimate on isopachs derived in this way.

In the USGS system, identified resources, within 4.8 km of a documented outcrop, would account for only a very small portion of the coal in the Transantarctic Mountains, probably not more than a few million tons. For this reason, we have not made a separate calculation of identified resources adjacent to each data point but have included this coal within resources calculated for the region. Because the vast majority of the coal calculated is beyond 4.8 km from an outcrop, we consider the whole figure to be an estimate of hypothetical resources.

Wood *et al.* [1983, p. 33] specify that estimates of coal quantity extend to a depth of 6000 ft (1800 m). In the Transantarctic Mountains we find this unrealistic for several reasons. First, the axes of the basins of deposition more or less parallel the trend of the mountain chain, which is the trend of the string of outcrops. The deeper coal lies to the west and south of the mountains, about at right angles to the trend of the axes of the basins of deposition and very probably across a change of facies into a basin margin facies. For this reason, we have kept the estimate closer to the outcrop and taken it to only a depth of 600 m. Because of the low dip of beds in most of the Beacon Supergroup, the projected 600-m depth of the coal measures is commonly as much as 7 km from the nearest outcrop. In addition, a depth of 600

m is the current practical limit for conventional underground room and pillar mining methods in the United States [Ferm and Muthig, 1982].

The hypothetical coal resource figures presented in this study were determined using the following formula:

$$R = A \times T \times C$$

where

- R* hypothetical coal resources for the Permian coal-bearing portion of the Beacon Supergroup;
- A* probable area of coal-bearing rocks determined in this study;
- T* total thickness of coal beds anticipated in the area based on information from measured sections;
- C* density factor allowing conversion from volume to metric tons.

The tonnage conversion factor used in this report to convert coal volume to weight depends upon the density of the coal in situ, which varies with apparent rank and ash content. In general, density increases with increased rank and/or ash content. Precise coal density data for the coals studied are sparse, and many of the analytical results on ash content are biased, because washing or gravity separation of samples prior to analysis decreased their density. Although much of the coal in the Transantarctic Mountains has an apparent rank of low-volatile bituminous coal or semianthracite, in this study we used a conservative conversion factor of 1,320,000 metric tons per square kilometer meter, the weight of bituminous coal 1 m thick over an area of 1 km² (modified from Averitt [1975, p. 21]).

Area of Coal Resource

As no map or map series delineates the area where Permian coal measures lie at a depth of less than 600 m (2000 ft), calculating this area required a series of approximations. Geology of the Transantarctic Mountains is shown on a series of five maps at the scale 1:1,000,000 published by the American Geographical Society [Gair *et al.*, 1969; Grindley and Laird, 1969; Warren, 1969; McGregor and Wade, 1969; Mirsky, 1969]. These maps show the approximate area of the Beacon Supergroup, but they do not delineate the area of coal measures. The 1:1,000,000 scale maps do not have topographic contours; they show geology of exposures and do not extrapolate into the subsurface. Using knowledge of the regional geology, available data on strike and dip in the Beacon, and knowledge of the topography, we estimated the areas in which the Beacon Supergroup may lie beneath 600 m or less of ice or rock. These areas were measured with a planimeter and found to be 54,000 km².

However, in the central Transantarctic Mountains, four geologic quadrangles at the scale 1:250,000 have

been published by the U.S. Geological Survey showing formations within the Beacon Supergroup including the Buckley Formation [Barrett *et al.*, 1970; Barrett and Elliot, 1973; Elliot *et al.*, 1974; Lindsay *et al.*, 1973].

Within each 1:250,000 scale quadrangle, available measurements of strike and dip of beds and topographic contours were used to estimate the areas in which the Permian coal measures lie within 600 m of the surface. The square kilometers of these areas were measured with a planimeter. In each 1:250,000 quadrangle it was found that the area of coal measures within 600 m of the surface equals 22–34% of the area of the Beacon Supergroup above that depth as estimated on the 1:1,000,000 map. Inasmuch as the Transantarctic Mountains consist of a system of similar mountains and valleys and pla-

teaus controlled in part by the stratigraphy of the Beacon Supergroup, we assume by analogy that a similar relationship obtains throughout the mountain chain. For this study we applied a conservative figure, assuming that coal measures lie beneath 25% of the area of Beacon Supergroup in the Transantarctic Mountains, beneath less than 600 m of cover. The derived map, showing areas where coal measures are considered to be within 600 m of the surface, is shown in Figure 7.

Isopach Map

The total thickness of coal in measured sections of coal-bearing rocks was contoured to produce an isopach map of total coal (Figure 7). The sediments in this

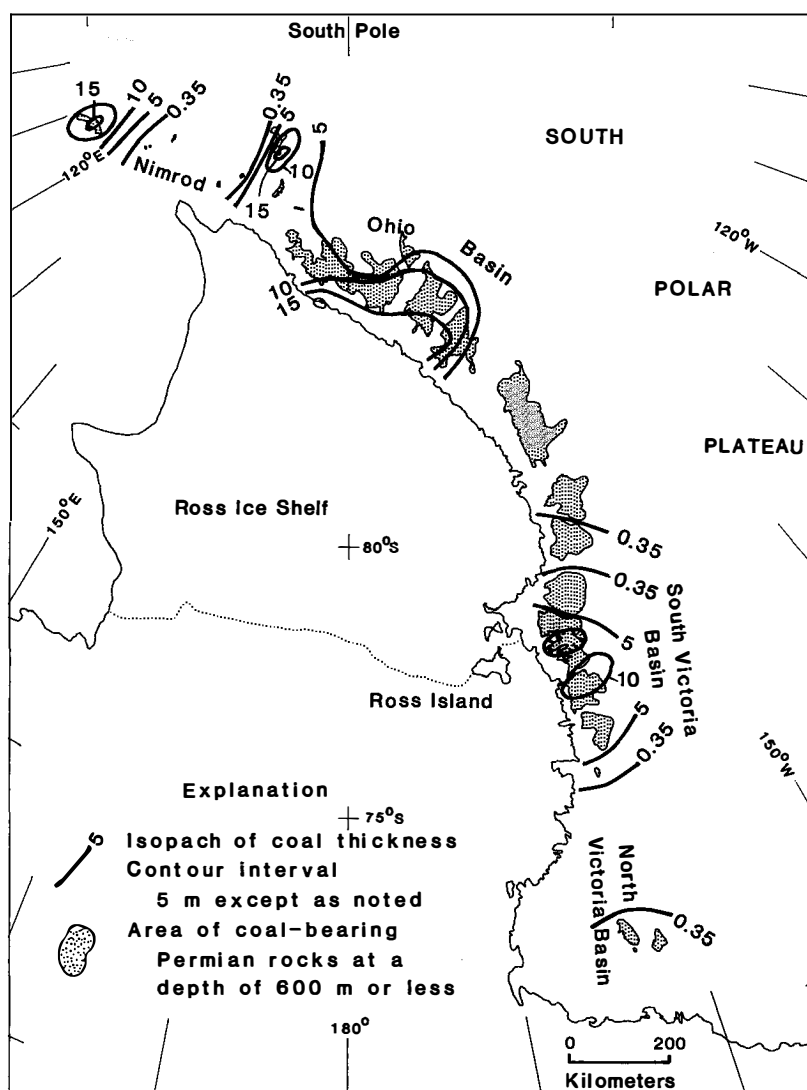


Fig. 7. Map showing areas where coal-bearing Permian rocks in the Transantarctic Mountains are estimated to be at a depth of 600 m or less and isopachs of total coal thickness.

sequence are fluvial, and most of the coal beds are not laterally continuous over large areas. In discussing estimates of coal quantities, *Rose and McElroy* [1987, p. 6] note: "It should be stressed that, in general, thicknesses recorded in the literature mostly refer to overall seam thickness, including bands of gray shale, carbonaceous shale and the like; the coal thickness in almost all cases is likely to be less than the stated seam thickness." Additionally, we must assume that as beds pinch and swell and split laterally, the localities that are exposed and where stratigraphic sections have been measured contain an average coal content for the region. Some authors include beds that they call impure coal, which might not be economically recoverable. On the other hand, there may be some coal beds less than 1 m thick that are not mentioned in reports or included in published measured sections but which nevertheless are thicker than the 35-cm minimum considered in conventional coal resource estimates.

In Figure 7 the coal isopachs clearly delineate the North Victoria Basin and the South Victoria Basin. Farther south, in the larger Nimrod-Ohio Basin, an area of thick coal extends from the Queen Elizabeth Range to the Scott Glacier. Between Scott Glacier and the Ohio Range (Figure 7), coal has not been found because the coal-bearing portion of the Beacon section has been removed by erosion. In the Ohio Range, outcrops are limited in number, but the section is thick.

Method of Calculation of Coal Resources

First, a map was created, using the procedure described above, showing the area underlain by coal measures at a depth of less than 600 m.

Second, an isopach map was made showing thickness distribution of total Permian coal in the study area. Beds thinner than 35 cm are generally excluded from resource considerations [*Wood et al.*, 1983].

Third, within areas mapped as having coal measures the area between each pair of isopachs was measured with a planimeter.

Fourth, volume of coal was calculated by multiplying area by the total thickness of coal, which was assumed to be the value half way between the bordering isopach contours.

Fifth, coal tonnage was calculated by multiplying volume of coal by a conversion factor of 1,320,000 metric tons per square kilometer meter.

Hypothetical coal resource estimates under less than 600 m of overburden in the three Permian coal basins in the Transantarctic Mountains are as follows:

<i>North Victoria Basin</i>	3 billion metric tons in beds as thick as 3 m
<i>South Victoria Basin</i>	47 billion metric tons in beds as thick as 6 m

Nimrod-Ohio Basin 100 billion metric tons in beds as thick as 10.7 m

Total estimated hypothetical resources for the Transantarctic Mountains

150 billion metric tons.

The following caveats accompany this estimate:

1. This estimate is hypothetical, which has low geologic assurance.
2. Isopachs were determined on total coal in the section; individual coal beds may be thinner than 35 cm.
3. Beds or parts of beds reported as coal may in fact be carbonaceous shales and not a resource.
4. Coal partings thicker than 1 cm, which properly are excluded from coal resource estimates [*Wood et al.*, 1983], almost surely have not been excluded from total coal thickness measurements in many cases.

SUMMARY AND RECOMMENDATIONS

Summary

Permian coals in the Victoria Group in the Transantarctic Mountains occur in three basins: the North Victoria Basin, the South Victoria Basin, and the Nimrod-Ohio Basin. Coal-bearing rock sequences in these basins are similar in gross sedimentary character; all contain coal that was deposited within an aggrading fluvial sedimentary system. The coal measures typically consist of repeated sediment units that begin with coarse or conglomeratic sandstone and fine upward into siltstone and shale, occasionally overlain by coal. Coal beds and coal zones have been correlated within some limited areas, but whether correlation is possible between basins is not known. In some areas, recent studies are revealing the three-dimensional stratigraphic architecture, but in most areas poor exposures or lack of intensive modern study leaves this unknown.

Rocks of the Victoria Group dip west and south beneath the polar plateau at angles of 0°–10°, and structure is generally simple. Faults, some with displacement as great as 3000 to 5000 m, are generally near vertical and have vertical displacement. In northern Victoria Land, fault trends are dominantly north-northwest, but in other parts of the Transantarctic Mountains the dominant trend is less apparent. Dolerite dikes intruded the whole Beacon Supergroup during the Jurassic.

Quality of coal samples analyzed and reported in the literature to date ranges widely. Rank ranges from meta-anthracite to high-volatile bituminous coal; in most areas studied the coal is mostly semianthracite to low-volatile bituminous coal. Sulfur content ranges from 0.0 to 4.8%, and the mean is 0.57%. Ash content ranges from 3.2 to nearly 50%, and the mean is 15.3%. Not enough studies of coal type have been done to characterize the coal by type.

Hypothetical estimates of Permian coal in the Transantarctic Mountains at a depth of less than 600 m are 150 billion tons. The amount of information available does not allow estimates of resources in a more reliable category.

Recommendations for Future Research

An integrated program of field and laboratory studies is needed to produce information about the Permian coals of the Transantarctic Mountains and the rock sequences that contain them. In order to be useful and internationally comparable, coal samples should be collected and analyzed using standard philosophy and techniques.

Almost all presently available information about the coals of Antarctica has been produced as accessory data during activities ranging from geographic exploration to stratigraphic research and geologic mapping. The information available about coal in almost all parts of the Transantarctic Mountains is inadequate, incomplete, or biased. Geologic assessment, "a critical analysis resulting in a judgment of the geologic nature, significance, status, quality, and quantity of the coal resources of an area . . ." [Wood *et al.*, 1983, p. 9], is not possible in any part of the Transantarctic Mountains with the presently available information.

Coal resource assessment studies needed in the Transantarctic Mountains fall into three broad, overlapping categories. The first category includes field description and sampling in those areas, such as the Freyberg Mountains (Figure 2, location 2), in which the presence of coal has been established, but the stratigraphic relationship of the coal relative to the sedimentary sequence is not well understood, and major questions remain about quantity and quality of the coals.

A second category includes field descriptions and sampling in areas where the sedimentary framework of the exposed rocks is reasonably well established, the stratigraphic position of coal has been documented, and a few gross samples have been collected and analyzed. In such areas, detailed stratigraphic relations, including extent, correlation, and geometry of coal beds or zones, have not been analyzed, and coal quality cannot be evaluated without further detailed sampling of both coal and associated rocks. An example of this category is from the Nimrod Glacier to the Beardmore Glacier area.

A third category includes such areas as parts of the Ohio Range and the South Victoria Basin, in which fairly detailed stratigraphic and structural information is available and standard procedures have been used to collect and analyze some coal samples. In these areas, detailed coal geologic studies are now possible. These studies should include field work designed to yield more detailed information about the coal than has been recorded in previously measured sections (the description

"coal, 1.6 m" is not adequate); to extend the recorded data laterally from measured sections by traverses, trenching, etc.; and to produce more detailed field descriptions and more detailed sampling of previously described sequences such as that exposed in the Dirty Diamond Mine [Long, 1964b].

The field studies should provide the stratigraphic and structural information required for geologic assessment and yield sample suites described completely by modern standards and accompanied by the required information about collection, philosophy, methodology, and techniques. The samples should be analyzed by standardized chemical and physical methods to provide the broad range of data needed for modern coal evaluation.

For example, a modern suite of coal quality analyses and determinations should include the following: (1) standard proximate analysis, supplemented by equilibrium moisture determination if the coal may be of low rank; (2) complete ultimate analysis; (3) heat of combustion determination; (4) determinations of forms of sulfur; (5) free-swelling index and other measures of agglomerating and caking properties; (6) a complete suite of ash-fusion temperatures under both reducing and oxidizing atmospheres; (7) grindability; and (8) apparent specific gravity.

In addition to the common analytical sequence described above, an analytical program for Antarctic coals should include major-, minor-, and trace-element analyses of the whole coal and associated rocks and of the coal ash. Such information is required for many applications in utilization technology. More importantly, this information is needed in predicting the environmental effects of coal usage.

Study of Antarctic coals is in its infancy. The detailed field observations and laboratory studies called for above will aid in predicting utilization possibilities and accompanying environmental impacts. However, as there is no immediate economic need for Antarctic coal, the most important studies will be those designed to delimit the Gondwana basins of Antarctica, the source areas of sediments, and the environments of deposition of the coals. Such reconstructions will contribute to understanding of the sedimentary systems of the ancient Gondwana continent.

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RECENT GEOPHYSICAL AND GEOLOGICAL RESEARCH IN ANTARCTICA RELATED TO THE ASSESSMENT OF PETROLEUM RESOURCES AND POTENTIAL ENVIRONMENTAL HAZARDS TO THEIR DEVELOPMENT

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During the 6-year negotiation of and adoption of the Convention on the Regulation of Antarctic Mineral Resources Activities on June 2, 1988, various countries have increased their attention to the possibility of exploitation of Antarctica's petroleum resources, which are covered by this treaty. However, there are no known petroleum resources in Antarctica, and scientific information is lacking to adequately assess any undiscovered resources or the possible environmental hazards to their development. Scientific research carried out in Antarctica since the International Geophysical Year (1957–1958) has provided a great deal of information on the geological framework of this ice-covered continent and its margin and has found general indications of the types of hazards that must be considered. Antarctica covers a vast area, and likely supergiant oil fields of the type to be exploited would be tiny (e.g., a few tens of kilometers across) in comparison. Any petroleum resources located in Antarctica will be found by applying the knowledge, techniques, and experience gained developing oil fields in other parts of the world and would, therefore, be other examples of general cases; in contrast, the Antarctic environment and its associated hazards must be considered unique.

INTRODUCTION

There is a great deal of interest (particularly outside the U.S. petroleum industry) in Antarctica's petroleum and mineral resource potential. The recently adopted Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA, which has not been ratified nor come into force) by the Antarctic Treaty Consultative Parties has stimulated new interest in Antarctica. However, there are no known petroleum or mineral resources in Antarctica (Figure 1), and no hard mineral deposits have been found that would be economically feasible even if they were present in more accessible parts of the world. Antarctic research, carried out primarily since the International Geophysical Year (IGY) 1957–1958, has provided a great deal of information on all aspects of Antarctica, not the least of which are results from basic geologic and geophysical studies which have application to petroleum resources and the environmental (meteorological, oceanographic, glaciological, and geologic) hazards that might impact their future development.

During the IGY, geology was one discipline conspicuously absent from Antarctic research probably because of possible political difficulties associated with the potential mineral resource aspects; mapping was specifically considered inappropriate [Quigg, 1983]. How-

ever, the USSR studied mineral resources and did considerable mapping [Quigg, 1983], and the United States conducted some mapping activities also. Nonetheless, the decade-long geophysical and glaciological oversnow traverse program started during that time and also provided a large amount of information on the surface and subsurface geologic structure of Antarctica. Geologic investigations have been carried out frequently by all of the countries in the Antarctic Treaty since IGY. Geologic and geophysical research can often be applied to both resource and environmental hazards assessment because the same type of data may provide evidence for either or for both. Behrendt [1983, 1990] discussed the scientific studies, including the 100,000 km of multichannel seismic reflection profiles (Figure 2) collected since 1976, relevant to Antarctica's petroleum resources and the environmental hazards connected with their safe development. In this paper I summarize these studies briefly, concentrating on the Ross Sea as an example, and include references from that report and new results. This research has concentrated primarily on geologic framework. There is little relevant information bearing on source or reservoir rocks, maturation conditions (however, see calculations by Hinz and Block [1983] and Davey [1985]), traps, etc.

The use of exploration techniques (or "prospecting,"

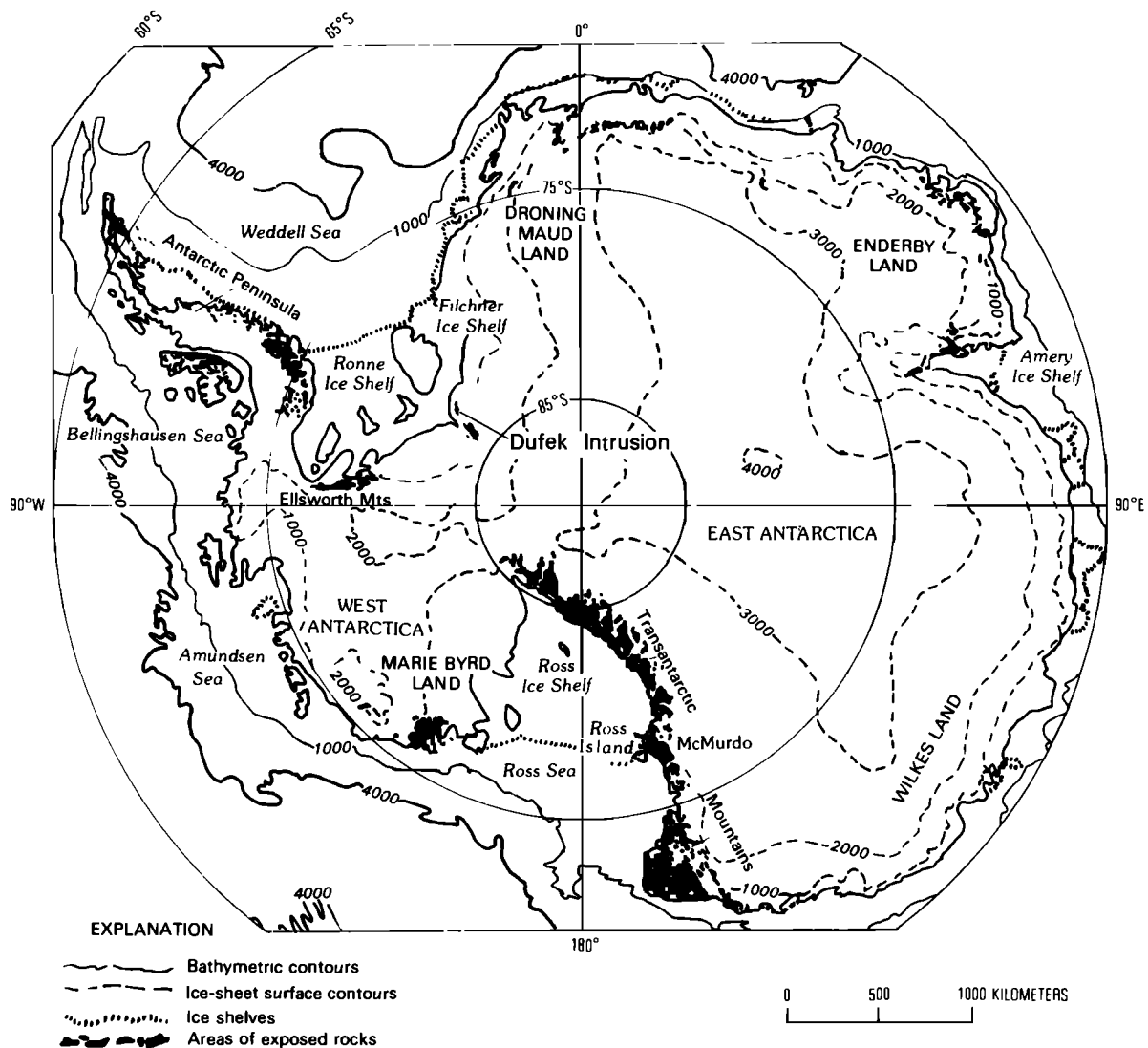


Fig. 1. Index map of Antarctica showing major geographic features discussed in text, including the continental margin. Bathymetric contour interval, 3000 m; ice sheet surface contour interval, 1000 m.

as used in CRAMRA) and geologic framework very similar to that occurring elsewhere in the world, where petroleum deposits have been found and economically developed, may be expected in Antarctica. However, the Antarctic environment is unique, and any future petroleum and mineral resource development will have to deal with its associated hazards as well as any potential adverse impact on the unique biota which inhabit it.

St. John [1986] discussed the hydrocarbon potential of Antarctica and estimated a potential hydrocarbon yield of 203 billion barrels (about 30 billion tons), based on a factor of about 1700 tons of hydrocarbon per cubic kilometer of sedimentary rock. I consider this an unre-

alistically, speculatively high value, particularly because B. St. John (personal communication, 1988) did not have available published interpretations of the seismic reflection data (Figure 2) to calculate sedimentary rock thickness because his interpretation was compiled originally in 1980. It is unfortunate that this value is being cited in the literature [e.g., *MacDonald et al.*, 1988] because I believe it raises unrealistic expectations. In contrast, early (1974) U.S. Geological Survey (USGS) estimates of undiscovered petroleum in Antarctica were never published because they were internally considered too speculative. They were variously reported [*Mitchell*, 1983; *Moorehouse*, 1986] as 45 billion barrels (about 6 billion tons), equivalent to recoverable

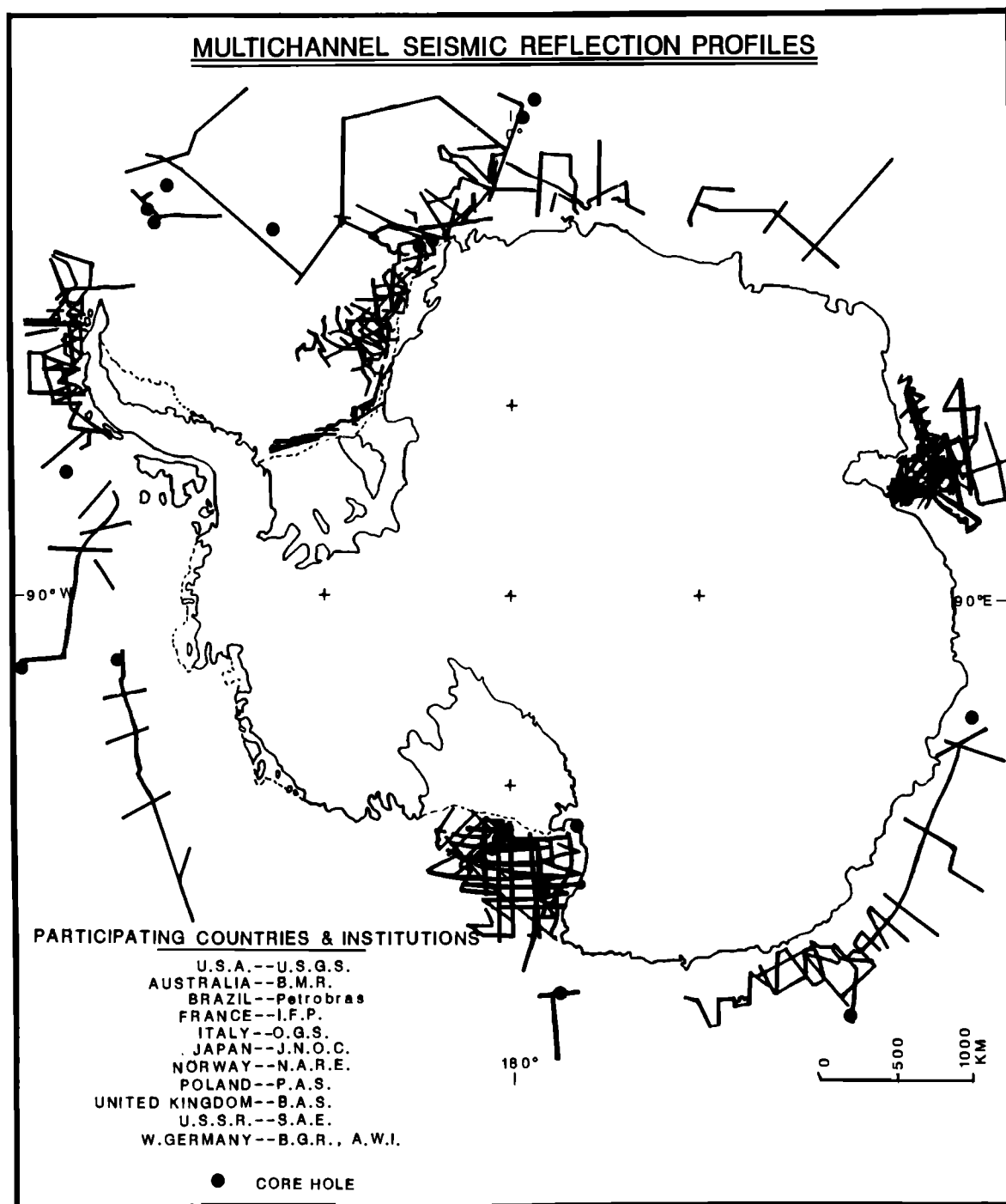


Fig. 2. Map of Antarctica showing locations of marine multichannel seismic reflection profiles collected through 1988.

reserves of 15 billion barrels (about 2 billion tons), or "in the magnitude of tens of billions of barrels" (C. D. Masters (1975), quoted by Mitchell [1983]). These values (although considered by USGS as "a reasonable

planning figure for the exercise at hand" [Mitchell, 1983]) are about an order of magnitude lower than those of St. John [1986]. More recently [Masters *et al.*, 1987], USGS published an estimate of 19 billion barrels (about

3 billion tons) at the 5% confidence level, which seems unrealistically low, considering the recently available information (e.g., Figure 2) cited in the references. These widely varying figures lead me to conclude (as have others [e.g., *Hinz and Kristoffersen*, 1987]) that there are insufficient data to make reliable estimates of undiscovered petroleum resources in Antarctica.

Antarctica is large (Figure 1), and potential mineral deposits are small in comparison. For example, the distance across Antarctica is comparable to that of Anchorage to Miami; by contrast, Prudhoe Bay, the only supergiant oil field in the United States, is only 56×5 km, Ghawar (Saudi Arabia) is 256×32 km, and Urengoi (USSR) is 140×90 km (B. St. John, personal communication, 1988). Therefore the difficulty of finding potential economic deposits in Antarctica is apparent considering the difficulty of conducting geophysical surveys in the harsh environment. It seems unlikely that any would be identified in the course of normal scientific research, although the understanding of the geologic framework necessary for mineral prospecting is being developed from this type of research.

Antarctica is high; the average elevation in East Antarctica is over 3000 m, reaching almost 4000 m in places. West Antarctica averages about 1500-m elevation. Antarctica is covered by a moving ice sheet, averaging about 3000 m thick. Only 2% of the bedrock in Antarctica is exposed. This projects through the ice as occasional small nunataks and other rather large extensive mountain ranges (Figure 1), all of which comprise competent rocks. Unmetamorphosed Mesozoic and Cenozoic sedimentary rocks would be expected almost exclusively beneath the ice sheet or continental shelves, and geophysical data [*Behrendt*, 1983, 1990] have indicated their presence in a number of areas of East Antarctica and West Antarctica, beneath the ice sheet.

Modern radar ice-sounding methods can be used to measure the thickness of the Antarctic ice sheet [*Drewry*, 1975, 1983]. This technique has been widely used in the last 15 years and has largely supplanted (over grounded ice) the more costly seismic reflection methods used prior to that time to measure depth to bedrock. In combination with the radio echo ice-sounding method, the aeromagnetic techniques provide probably the best quick and simple remote sensing tools with which to study the geology of Antarctica beneath the ice sheet [e.g., *Behrendt et al.*, 1980; *Jankowski et al.*, 1983]. This method allows the extension of geological knowledge obtained with great difficulty at widely spaced rock outcrops to subglacial areas.

Although variously spaced aeromagnetic traverses have been made in Antarctica since the 1950s, the first standard aeromagnetic survey in Antarctica (e.g., contour interval of 5 nT) was carried out by the Federal Republic of Germany, Bundesanstalt für Geowissenschaften und Rohstoffe, and the USGS in north Victoria

Land and the Ross Sea in the 1984–1985 field season [*Behrendt et al.*, 1990; *Bosum et al.*, 1989, 1990].

Since 1976, marine multichannel seismic measurements have been made along about 100,000 km of profiles by researchers from at least 11 countries across Antarctic continental margins (e.g., Figure 2). Marine multichannel seismic methods are very much more expensive and difficult to apply in Antarctica than the earlier single-channel profiling methods used by research ships, because a long streamer up to 3 km in length must be towed behind the ship in ice-free areas.

By combining the results of various types of investigations, researchers have a general idea of the locations of basins containing thick sedimentary rock. *Behrendt* [1990] showed a generalized version of subice topography, major topographic features, and regional sedimentary basins which would be the likely focus for prospecting for petroleum resources under CRAMRA. Although Antarctica is covered by a moving ice sheet about 3 km thick, probably petroleum could be safely produced from underlying basins. Because of the order-of-magnitude lower expense of collecting multichannel seismic reflection data from a ship compared with oversnow surveys, the continental margins would be the likely areas for earliest future petroleum development. The West Antarctic continental shelves of the Weddell, Bellingshausen, Amundsen, and Ross seas are the most promising areas. However, the Amery Ice Shelf area (Figure 1) of East Antarctica, probably overlying an aulocogen, is considered the most likely there.

PETROLEUM RESOURCES IN THE ROSS SEA

I will use the Victoria Land basin in the Ross Sea as an example of the type of research that would be needed for petroleum resource assessment and then indicate the type of environmental hazards that might be encountered in this area or other areas of Antarctica. *Behrendt* [1983, 1990] and *Hinz and Kristoffersen* [1987] discuss some results of the work indicated elsewhere (Figure 2) over the Antarctic margin.

Figure 3 shows the extensive multichannel seismic surveys (about 35,000 km) in the Ross Sea carried out by the United States, the Federal Republic of Germany, France, Japan, and the USSR [*Behrendt*, 1990]. As a result of this and earlier seismic refraction and single-channel reflection surveys, three basins (Figure 4) have been identified beneath the continental shelf. These are part of the West Antarctic rift system [*LeMasurier*, 1990] which extends south and east into largely ice-covered Marie Byrd Land. Figure 5, from *Cooper et al.* [1987], indicates the seismic interpretation of a USGS seismic section across the Victoria Land basin, the westernmost of the three. The age of the geologic strata shown in Figure 5 is extrapolated from the Deep-Sea Drilling Project (DSDP) drill holes (Figure 3) to the east

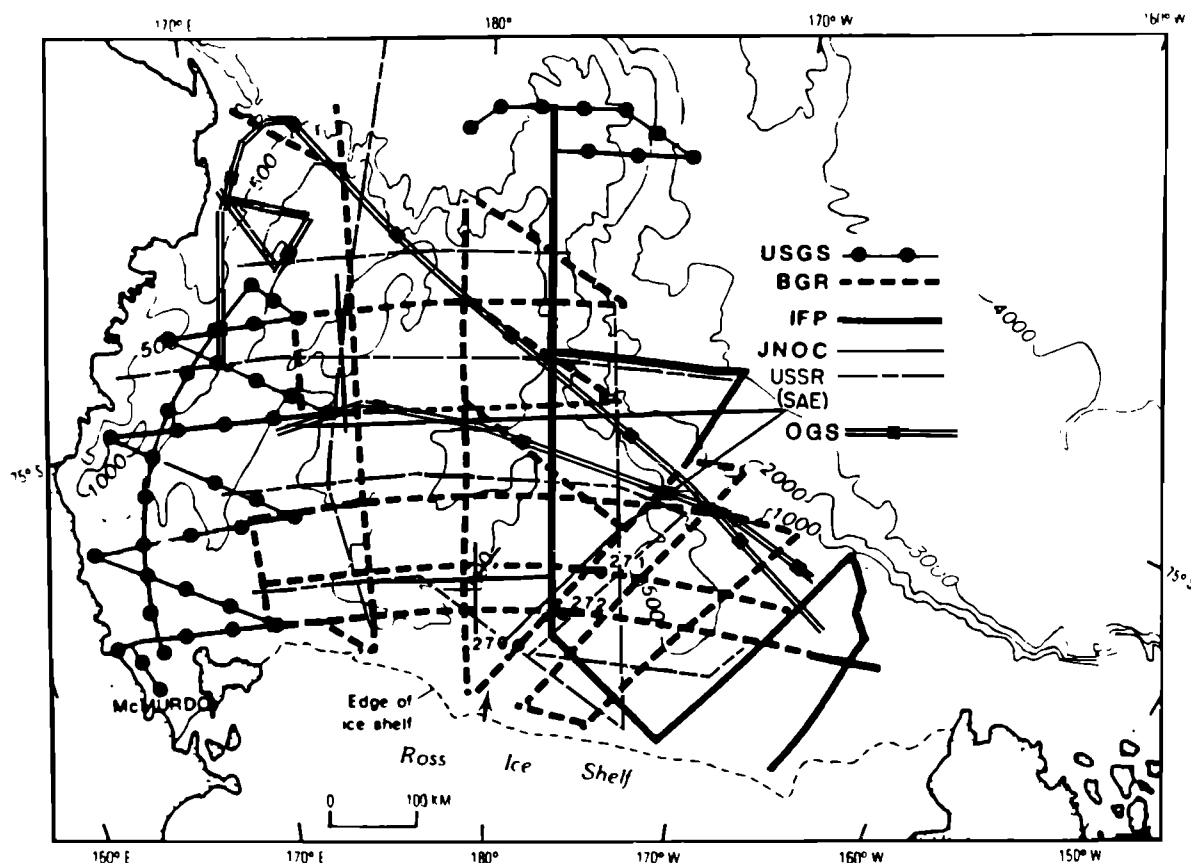


Fig. 3. Map showing location of multichannel seismic reflection surveys in the Ross Sea. Bathymetry is in meters. DSDP holes 270, 271, and 272 and line 407 are indicated.

[Hayes and Frakes, 1975] and the MSSTS-1 hole to the south [Webb, 1983] and approximately tied by the multichannel seismic data reported by Hinz and Block [1983] and Cooper *et al.* [1987]. The CIROS I drill hole near McMurdo (Figure 3) found evidence of hydrocarbon (asphaltic residue) at 632-m depth. Barrett and Cook [1987] interpreted this result to show that oil and gas were once trapped there but subsequently leaked out. In another area (Weddell Sea coast of the Antarctic Peninsula, Figure 1), MacDonald *et al.* [1988] reported a moderate potential for oil generated from Upper Jurassic source rocks. Future drilling would be needed to provide more information on source rocks, traps, and reservoirs as well as stratigraphic age to make petroleum resource evaluations.

These examples illustrate the types of research that can lead to an understanding of the geologic framework of the area relevant to resource assessment. They have not led to the identification of any specific prospects for an oil exploration; only detailed surveys and drilling could do that.

ENVIRONMENTAL HAZARDS

Antarctica has the most severe environment on Earth in which to carry out petroleum exploration or exploitation. The justifiable concerns expressed by CRAMRA about serious degradation to marine biota that could be caused by offshore petroleum development have focused attention primarily on the ecosystem. The possible accidents that could cause damage to the ecosystem would be largely the result of the hazardous Antarctic environment on human activities. Various groups (such as Group of Experts [1977], Zumberge [1979b], and Holdgate and Tinker [1979]) have attempted to deal with potential environmental problems and to suggest research areas. Generally, these reports have concentrated on climatological, oceanographic, and glaciologic hazards and the vulnerable Antarctic ecosystems that might be affected while largely ignoring the geologic hazards that could actually lead to blowouts and oil spills. Were exploration drilling and exploitation to occur, much research in specific geographic areas would

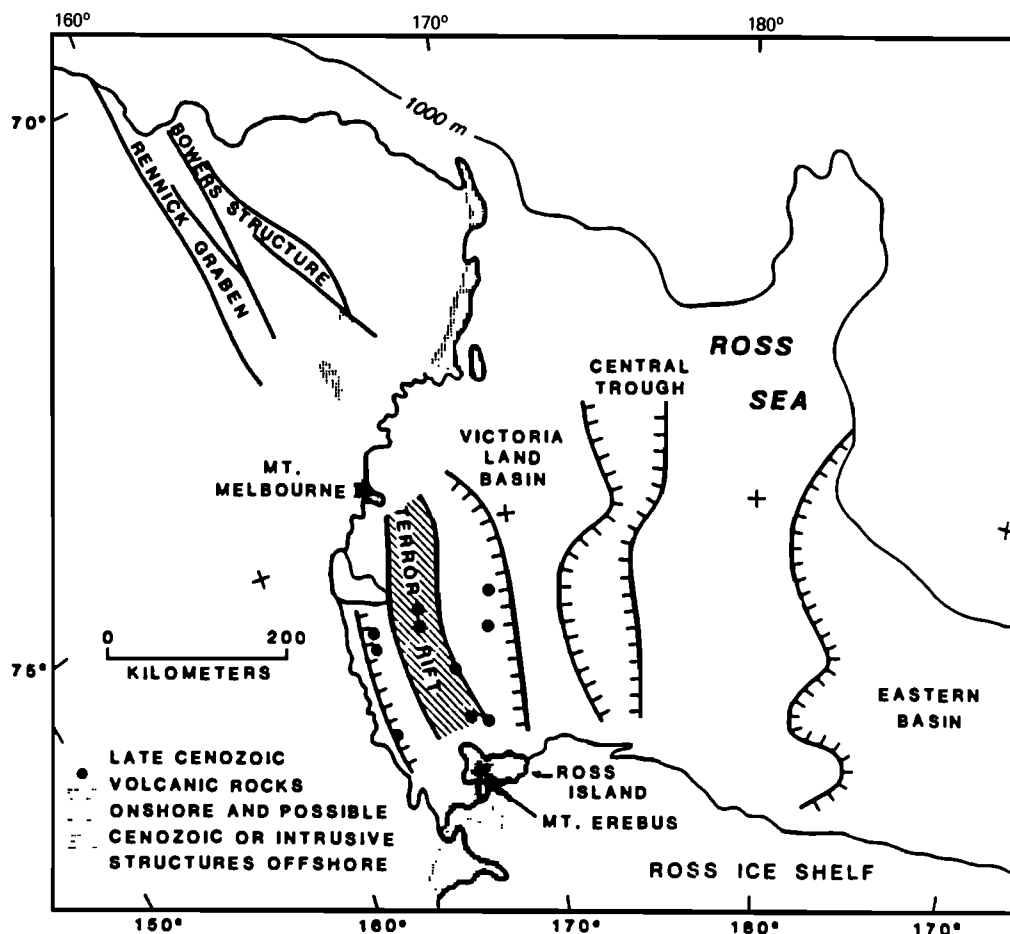


Fig. 4. Map showing approximate location of structural features in the Ross Sea region [from Cooper *et al.*, 1987].

be required into the types of hazards that might be encountered as well as the ecosystem that might be disturbed.

Research ships carrying out multichannel seismic reflection surveys over the continental margin in Antarctica normally carry out a number of other studies as well, such as high-resolution seismic reflection profiling, seismic refraction studies, side-scan sonar, shallow coring (less than 5 m), hydrocarbon analyses, etc. The results of the *S. P. Lee* described in the two volumes by *Eittreim and Hampton* [1987] and *Cooper and Davey* [1987] provide a number of examples of this multidisciplinary approach.

Mount Melbourne and Mount Erebus, along the west side of the Ross Sea, are examples of active volcanoes associated with the West Antarctic rift system [*LeMasurier*, 1990]. There are numerous other outcrops of Cenozoic age volcanoes, extending along the west coast of the Ross Sea (Figure 4), which have erupted during the last 19 million years. The geophysical surveys of the

S. P. Lee found examples of penetrative structures interpreted as inferred Cenozoic intrusions extending through the sedimentary rocks in the Victoria Land basin (Figure 5). These have short-wavelength high-amplitude magnetic anomalies associated with them [*Behrendt et al.*, 1987] and might indicate potential volcanic and other neotectonic hazards to operations on the seafloor above the Victoria Land basin. Ash layers exposed in the ice front of glacial tongues near Mount Melbourne indicate recent volcanic eruptions within the last 50 years as suggested by *G. Wörner and L. Viereck* (1989). Aeromagnetic anomalies [*Behrendt et al.*, 1990] that were observed over Mount Melbourne and Mount Erebus show a good correlation with these active volcanoes. Short-wavelength magnetic anomalies indicate the presence of about 100 inferred volcanic structures in the Victoria Land basin (Figure 4) area. A number of these interpretations were substantiated by the seismic reflection profiles collected by the *S. P. Lee* in 1984 [*Behrendt et al.*, 1987]. Some of the interpreted volcanic

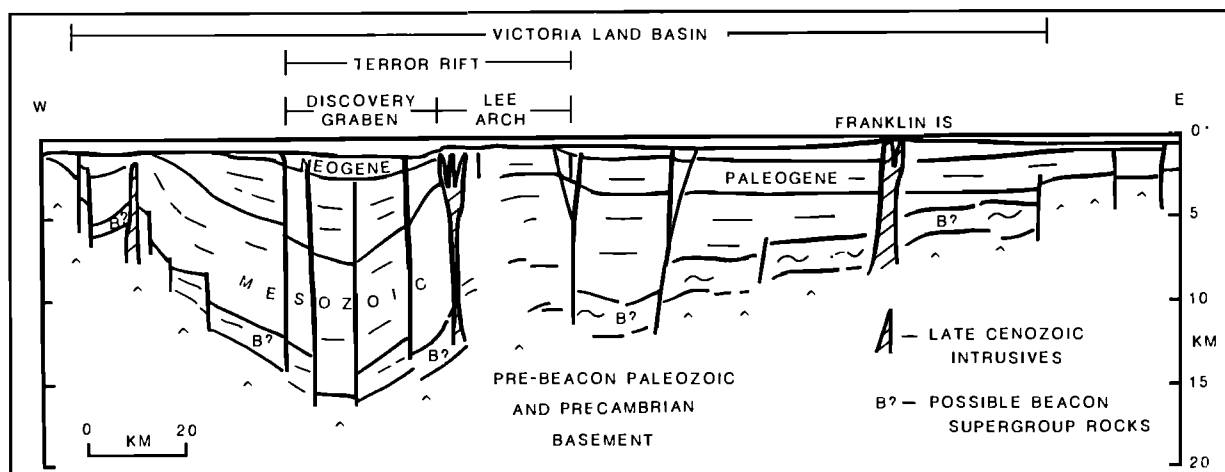


Fig. 5. Interpretive stratigraphic model for ages of rocks in the Victoria Land basin. Cross section is based on interpreted depth section for line 407 (Figure 3) [from Cooper *et al.*, 1987]

features on the sea bottom appear younger because of their topographic expression [Behrendt *et al.*, 1987] than latest glaciation (less than 20,000 years) and further support the idea of active volcanism in this area.

High-resolution (3.5-kHz) bathymetric profiles measured along the multichannel seismic lines and other seismic lines showed evidence of fault scarps in the Victoria Land basin area [Behrendt, 1990]. This is another example of the type of surveys that are needed to identify hazards associated with active faulting which might displace pipelines or structures placed on the sea bottom.

One of the most significant hazards to petroleum development on the Antarctic continental margin is collision with icebergs. Bergs can damage a drilling rig at the sea surface or damage supporting structures, pipelines, and other seafloor structures when scraping along the sea bottom. High-resolution profiles in the western Ross Sea [Karl *et al.*, 1987] suggest iceberg scour has occurred there. Side-scan sonar data collected by the *S. P. Lee* along the Wilkes Land margin [Barnes, 1987] showed good examples of iceberg scour even in water depth exceeding 500 m. Barnes [1987] interpreted the data on the Wilkes Land margin as evidence of modern iceberg scour. Previously, the Norwegian Antarctic research expedition [Fossum *et al.*, 1982] reported deepwater iceberg scour in the Weddell Sea area. Although this scour is possibly relict from older glaciation, the burden of proof would be on the potential developer to secure enough geophysical and geological data on iceberg scour in a particular area and demonstrate the age of the features before petroleum development on the seafloor in such an area could be considered safe. Remote sensing data from space can reveal iceberg frequency and size which will aid in studying this problem. Radio echo sounding profiles over floating

icebergs in the sea in the area to be considered for petroleum development can be used to estimate thickness and consequently the likelihood of seafloor scour.

Finally, this noninclusive list of hazards should include the presence of gas hydrate, which might be expected beneath the ≥ 500 -m-deep continental shelf of Antarctica. Gas hydrates are solid, crystalline, icelike combinations of water and gas (commonly methane) that form within the sediments. The presence of gas hydrate is usually interpreted from bottom simulating reflections (BSR), unrelated to geology, that parallel the seafloor in seismic reflection profiles. The only area of the Antarctic margin where BSR have been observed is off Wilkes Land. Kvenvolden *et al.* [1987] reported several examples and concluded that gas hydrate was present in this area. Although the presence of gas hydrate in a particular area might at first appear as evidence for a resource there, I believe the environmental hazards associated with it would outweigh the potential resource value. The hydrate may act as a seal, keeping oil or gas from escaping into the ocean. Drilling or development activities could disrupt the seal and release large amounts of hydrocarbons (explosively?) into the marine environment. Therefore the presence of any BSR in a particular area should be considered as evidence of gas hydrate and be treated with caution. The absence of the BSR in an area would not prove the absence of gas hydrate, and drilling would have to proceed cautiously to examine the cores for evidence of gas hydrate. By analyses of the hydrocarbons present, the DSDP cores collected in the Ross Sea suggested that gas hydrate could be present there [Rapp *et al.*, 1987].

SUMMARY

In this brief discussion of research related to petroleum resource assessment and environmental hazards

assessment studies in Antarctica, I wish to emphasize the following:

1. Antarctica is an immense ice-covered area, and potential mineral resource deposits are extremely small in comparison. Finding them will be very difficult, even unlikely. Only very detailed geophysical surveys and geologic mapping will enable such deposits to be located. At present, there are insufficient data to make reliable estimates of undiscovered resources beneath the Antarctic continental margin.

2. Some of the same types of studies that are commonly used for petroleum exploration (e.g., multichannel seismic reflection and aeromagnetic surveys) might also reveal environmental hazards. In general, however, different types of surveys (e.g., high-resolution seismic profiling, shallow coring, etc.) will be needed to study the environmental hazards. Release of these data would not compromise a potential developer's economic advantage over a competitor. In fact, these are the types of surveys that would provide the "sufficiency of information" required under CRAMRA.

3. When deposits have been identified by geophysical and geological surveys and are proposed for exploration and development, careful environmental surveys such as those briefly described in this paper will be necessary before they can be approved.

4. Any petroleum and mineral resources located in Antarctica will be found by applying the knowledge, techniques, and experience gained in the other parts of the world where mineral and petroleum development has already occurred because only the largest and most typical types of deposits would be sought. In contrast, the Antarctic environment must be considered unique. Even though the techniques might be similar to those developed elsewhere, petroleum development in Antarctica will require special research efforts and technology that are not commonly used in other parts of the world.

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GEOLOGY AND HYDROCARBON POTENTIAL OF THE ANTARCTIC CONTINENTAL MARGIN

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Seismic surveys have been conducted on most of the seasonally ice-free portions of the Antarctic continental margin, but drilling has been limited to only a few areas. These data, coupled with the results of geological studies of coastal outcrops and information from the conjugate Gondwana continents, are used to infer the subsurface geology of five different sectors of the Antarctic continental margin and to assess their hydrocarbon potential. Potential source rocks are believed to exist on most portions of the continental margin and are buried deep enough, or are subjected to high enough geothermal heat, for hydrocarbon maturation to have occurred in these deposits. Suitable reservoir rocks are also considered to be widespread on the margin, with the possible exception of that portion of the Pacific-Antarctic margin situated north of the Tula Fracture Zone and including the Bransfield Basin. Structural traps are generally confined to the older sequences on the margin that fill early rift basins. Stratigraphic traps are probably common.

INTRODUCTION

The Antarctic continental shelf has an average water depth that ranges between 400 and 800 m and is covered by sea ice during most of the year. Huge icebergs with drafts of several hundred meters drift freely on the shelf, and the seas that surround the continent are among the roughest in the world. The shelf is also quite rugged and is floored by Quaternary glacial and glacial-marine deposits whose geotechnical properties vary widely over relatively short distances. These combined conditions make the Antarctic continental shelf one of the most unsuited regions of the world for hydrocarbon exploitation. Nevertheless, the vast continental margin of Antarctica has long been considered a suitable location for large oil fields, and interest in possible exploitation of the continent's hydrocarbon reservoirs is growing as political constraints on exploration are eased.

This paper presents an assessment of potential oil and gas reserves on the Antarctic continental margin. Since drilling there has been limited, this assessment is based largely on extrapolations drawn from marine geophysical surveys, the geology of neighboring Gondwana continents, and information gained from geological studies of Antarctica's coastal regions. For purposes of discussion, the continental margin is divided into five different sectors (Figure 1) based upon the prebreakup and postbreakup history of the continental margin.

WILKES LAND SECTOR

Geology

Prior to the breakup of Gondwana, the Australian and Antarctic continents were joined along what is now the Wilkes Land continental margin of Antarctica (Figure 2). Initial studies of magnetic data from the Indian Ocean by *Weissel and Hayes* [1972] led to the conclusion that seafloor spreading between Australia and Antarctica began 55 million years ago. Later, *Cande and Mutter* [1982] reinterpreted these data and concluded that initial rifting between the two continents had actually begun between 110 and 90 Ma, and *Veevers* [1986] constrained the time of breakup to 95 ± 5 Ma. Actual breakup was preceded by an extended period of extension and rifting, which *Falvey* [1974] refers to as the Rift Valley Phase. This phase probably began in the mid-Jurassic [*Veevers*, 1987]. During this time, rift basins formed in the vicinity of the incipient breakup axis. Initially, these basins were broad troughs which developed into narrow fault-bounded basins as rifting progressed [*Falvey and Mutter*, 1981]. Subsidence rates on Australia's southern margin were high (an average of 0.1 km/Ma) during the rifting phase and slowed appreciably (an average of 0.01 km/Ma) during the post-breakup phase [*Falvey and Mutter*, 1981]. During the rifting phase, a thick sequence of mostly continental deposits accumulated in the basins of southern Australia, with periodic marine invasions from the west result-

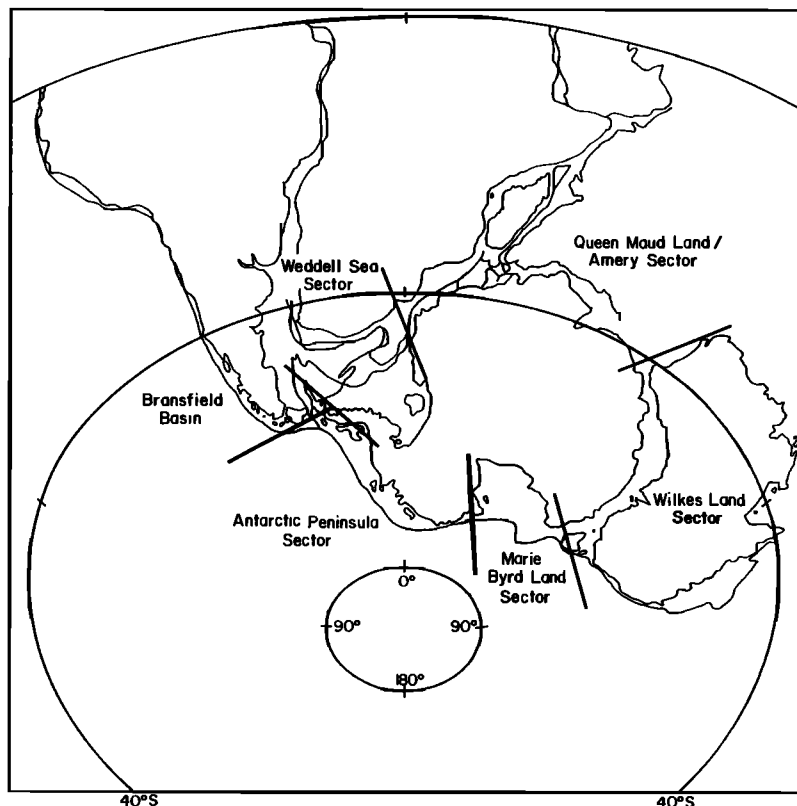


Fig. 1. Reconstruction of the Gondwana continent at 115 Ma [after Norton and Sclater, 1979] showing different sectors of the Antarctic continental margin that are described in this paper.

ing in marginal marine deposition in basins that now occupy the southwestern portion of the margin (e.g., Eucla Basin) during Aptian/Albian time [Deighton *et al.*, 1976]. To the east, rift basins were filled with a monotonous sequence of continental deposits consisting mainly of sandstone and mudstones. Up to 9 km of prebreakup deposits occur in the Great Australian Bight Basin [Falvey and Mutter, 1981].

Although the Wilkes Land sector of the Antarctic margin has not been drilled, there is abundant evidence that Cretaceous deposits similar to those of the southern Australian margin underlie the present continental shelf. Truswell [1982] conducted a palynological analysis of samples acquired from the East Antarctic continental shelf by Douglas Mawson during the Australian Expedition of 1911–1914. Samples from the Wilkes Land and George V Land continental shelves include lignites that contain abundant pollen and spores ranging in age from early Cretaceous to early Tertiary. A piston core collected in the Mertz-Ninnis Valley, situated offshore of George V Land, during Deep Freeze 79 penetrated an outcrop of mudstone with abundant pollen and spores of Aptian age, but lacking marine microfossils [Domack *et al.*, 1980]. Detailed analysis of the pollen and spore assemblage in this core showed it to be identical to that

of early Cretaceous deposits of the Otway Basin of southern Australia [Domack *et al.*, 1980].

Early postbreakup (late Cretaceous) deposition on the southern Australian margin is characterized by gradual marine deepening with deposition of a “transgressive-regressive series of sands, silts, and muds” [Deighton *et al.*, 1976]. During the Paleocene and early Eocene, marine transgressions were more widespread in southern Australia, although these marine deposits are relatively thin [Boeuf and Doust, 1975]. There is no record of carbonate or evaporite deposition during the early postbreakup interval. Truswell [1982] argues that re-worked late Cretaceous-Eocene palynomorphs from the Wilkes Land and George V Land continental shelves of Antarctica indicate a similar setting to that of southern Australia at this time; predominately continental deposition with occasional shallow marine incursions indicated by dinoflagellates.

The close parallel between the Antarctic and Australian continental margins ends with the onset of carbonate deposition on the southern Australian margin commencing in middle Eocene to early Oligocene [Falvey, 1974]. In Antarctica this was a period of pronounced cooling and initial development of an ice sheet on the continent [Barron *et al.*, 1989] and destruction of land

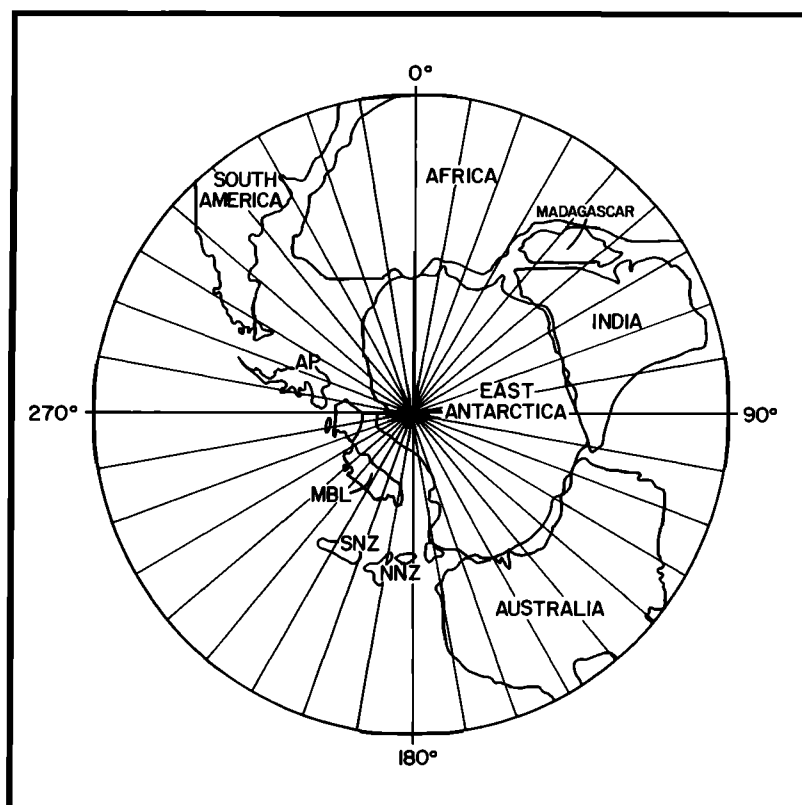


Fig. 2. Early Mesozoic reconstruction of Gondwanaland [from Lawver and Scotese, 1987]. AP, Antarctic Peninsula; MBL, Marie Byrd Land; SNZ, southern New Zealand; and NNZ, northern New Zealand.

vegetation as indicated by an absence of reworked palynomorphs of this age [Truswell, 1982].

Domack [1987] developed a stratigraphic model for the continental shelf of George V Land based on petrographic information derived from piston cores that penetrated Quaternary glacial and glacial-marine deposits on the shelf. Glacial sediments from the northern flank of the Mertz-Ninnis Trough, a deep glacial trough on the inner shelf, contain abundant quartz, stable heavy minerals, and sandstone clasts and imply that sandstones subcrop in the area. These sandstones are likely overlain by dolerite or basaltic intrusives, possibly related to rifting. Arkosic sandstones are believed to subcrop on the outer continental shelf, but their stratigraphic relationship to the sandstones and intrusive rocks of the inner shelf is uncertain.

Seismic reflection surveys of the Wilkes Land sector of the continental margin have been conducted by French [Wannesson *et al.*, 1985], U.S. [Eittreim and Hampton, 1987], and Japanese [Saki *et al.*, 1987] scientists. Only segments of the French and Japanese profiles have been published, but more detailed information on the region can be found in the work of Eittreim and Hampton [1987].

Hampton *et al.* [1987] have inferred styles of post-breakup deposition on the Wilkes Land continental margin from seismic reflection data acquired during a survey by the U.S. Geological Survey. They recognize an older sequence (sequence C) resting on the breakup unconformity (Figure 3) and interpret it as consisting of continental and shallow marine deposits. This sequence is overlain by a younger sequence (sequence B) of deep marine sediments which onlap the older sequence and suggest pronounced deepening of the seafloor. The youngest sequence (sequence A) includes channelized fan deposits.

Profiles acquired by Wannesson and his colleagues (Figure 3) show more than 6 to 7 km of sedimentary deposits resting on the block-faulted continental basement of the Wilkes Land continental shelf. Three sequences are recognized, and the bulk of these deposits are assigned a late Eocene and younger age by Wannesson *et al.* [1985]. However, these ages are inconsistent with the geological history outlined above. The combined data from these geophysical surveys and the geological information deduced from the southern Australian and the Antarctic continental margins are summarized in the idealized marginal profile shown in Figure 4.

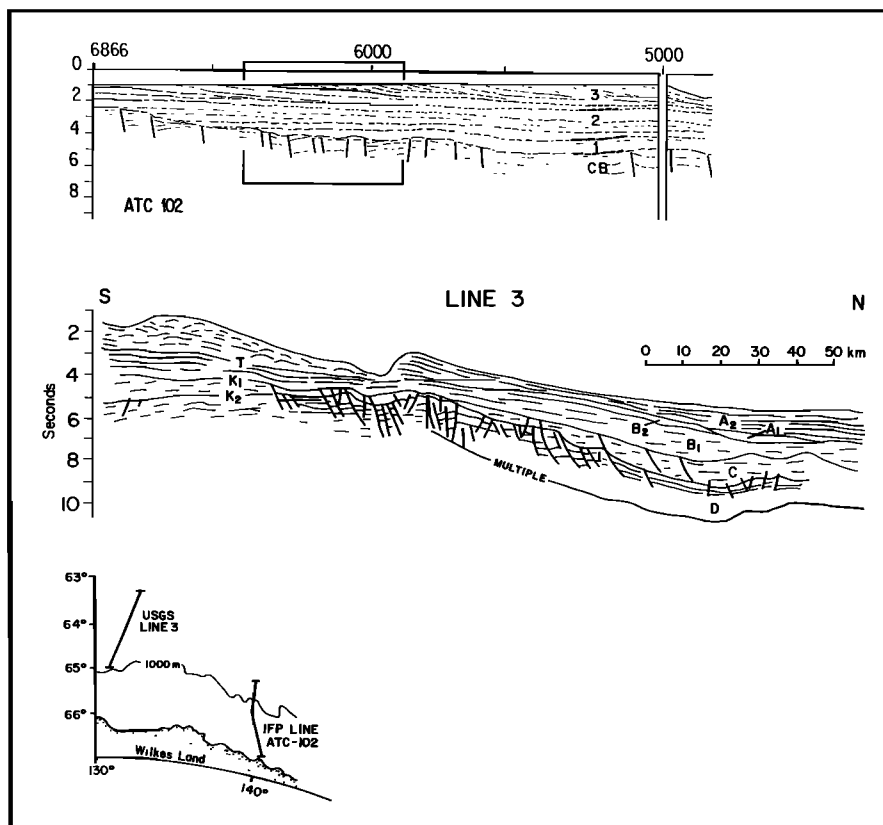


Fig. 3. Interpreted seismic reflection lines from the Wilkes Land continental margin. Line ATC 102 is from Wannesson *et al.* [1985], and line 3 is from Eittrheim and Hampton [1987].

Hydrocarbon Potential

Thick sedimentary sequences occur on the Wilkes Land continental margin. Potential source rocks include Cretaceous carbonaceous shales, but it is not known whether these deposits have been buried deep enough to generate hydrocarbons. Maturation models, such as the model of Waples [1980], have not been applied to this sector because heat flow data are lacking.

As evidenced by the work of Domack [1987], reservoir and cap rocks are probably widespread on the continental shelf. Except in the older rift phase deposits, structures into which these hydrocarbons could migrate are virtually absent. If significant petroleum deposits occur, they are probably associated with stratigraphic traps.

Indirect evidence of the presence of gas hydrates on the Wilkes Land continental margin exists in the form of bottom-simulating reflectors (BSR) in multichannel seismic records; otherwise, geochemical studies have failed to yield evidence for significant hydrocarbons on the margin [Kvenvolden and Cooper, 1990].

QUEEN MAUD LAND/AMERY SECTOR

Geology

Prior to the breakup of Gondwana, the eastern margin of India/Sri Lanka and the southeastern margin of Africa were situated adjacent to that portion of East Antarctica between 100°E and 25°W (Figure 2), which is referred to here as the Queen Maud Land/Amery Sector (Figure 1). Therefore the prebreakup geology of this sector of the Antarctic margin should resemble that of its Indian/Sri Lankan and South African counterparts. In the Cauvery, Palar, and Godavari-Krishna basins of eastern India/Sri Lanka, prerift and early rift phase deposits consist of nonmarine to marine sandstones, shales, and limestones [Salni, 1982].

The geology of South Africa is dominated by folded mid-Paleozoic rocks of the Cape Supergroup and late Paleozoic to early Mesozoic rocks of the Karoo Supergroup. Jurassic volcanic rocks are also widespread. The east-west trending Cape Fold Belt is the prominent structural feature in South Africa. The Cape Supergroup

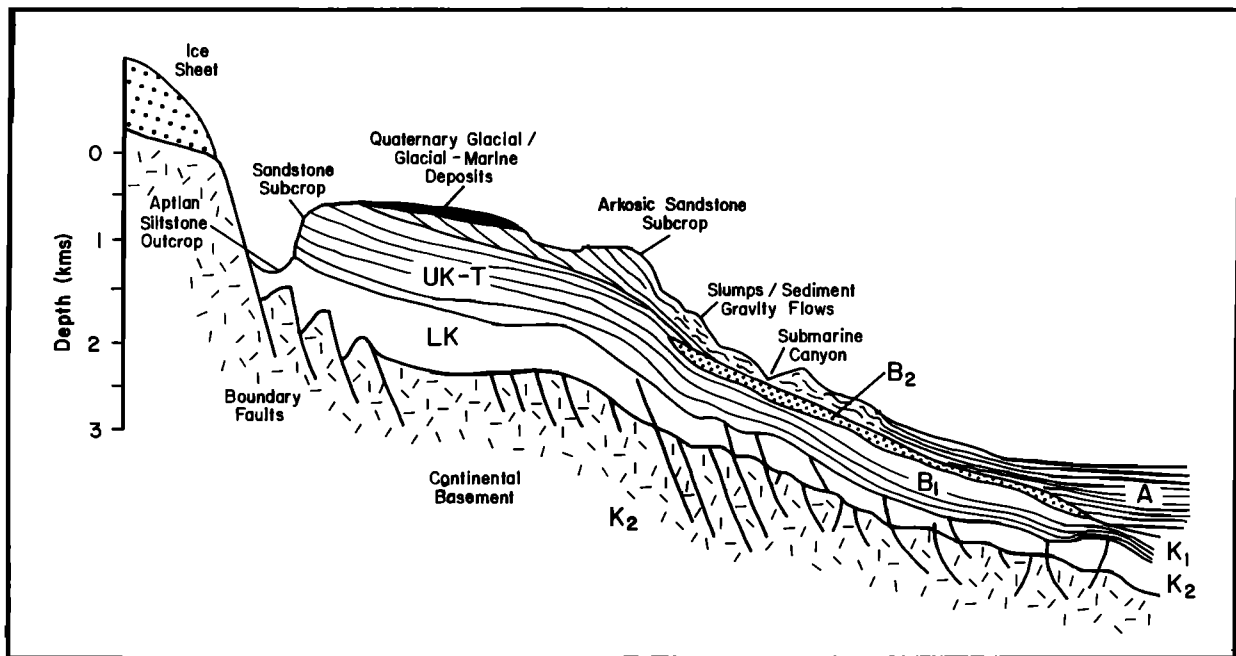


Fig. 4. An idealized geological profile of the Wilkes Land continental margin based on combined data from geophysical surveys and geological information deduced from the southern Australian and the Wilkes Land margins. Seismic sequences (K_2 , K_1 , B_2 , B_1 , and A) are from *Eitrem and Hampton* [1987]. LK, Lower Cretaceous; UK-T, Upper Cretaceous through Tertiary. (See text for discussion.)

rocks, dominantly sandstones, were deposited along a subsiding margin of a broad cratonic shelf, with depocenter trending parallel to the present coast. The oldest Karoo rocks are the Permo-Carboniferous Dwyka glacial deposits. These are overlain by Permian shallow marine deposits (Ecca Group) and Triassic fluvial deposits (Beaufort Group). The Karoo rocks are remarkably similar to rocks of the same age in the Ellsworth Mountains and Pensacola Mountains of Antarctica.

Initial separation between Africa and Queen Maud Land began approximately 150 Ma [Bergh, 1987], and separation between India/Sri Lanka and Antarctica began between 130 Ma and 118 Ma [Johnson *et al.*, 1976; Katz, 1978; Lawver and Scotese, 1987]. By early Cretaceous time (115 Ma), separation had occurred between Antarctica and Africa and India/Sri Lanka, marking the inception of independent stratigraphies for these continents.

Geophysical studies of the Queen Maud Land/Amery Sector of the continental margin have been conducted in the area of Prydz Bay and the Mac. Robertson Land continental shelf [Stagg *et al.*, 1983; Stagg, 1985; Mizukoshi *et al.*, 1986] and off eastern Queen Maud Land [Hinz and Krause, 1982; Saki *et al.*, 1987]. Four Ocean Drilling Project (ODP) sites were drilled on the continental shelf in Prydz Bay during Leg 119 [Barron *et al.*, 1989], and three sites were drilled on the Queen Maud

Land margin in the northeastern Weddell Sea during ODP Leg 113 [Barker *et al.*, 1988].

The results of a multichannel seismic reflection survey conducted by the Australian Bureau of Mineral Resources during 1981–1982 show that Prydz Bay is situated within a sedimentary basin, the Prydz Bay Basin [Stagg *et al.*, 1983; Stagg, 1985]. This basin appears to be the offshore portion of a more extensive feature, the Lambert Graben, which extends some 700 km beneath the Amery Ice Shelf and Lambert Glacier [Wellman and Tingey, 1976; Kurinin and Grikurov, 1982; Fedorov *et al.*, 1982]. The Lambert Graben and Prydz Bay structure are believed to be a failed arm of a triple junction associated with initial breakup of India/Sri Lanka and Antarctica at approximately 130 Ma [Johnson *et al.*, 1976] and possibly connect with the Mahanadi Graben of India [Fedorov *et al.*, 1982]. The NE-SW orientation of the Prydz Bay Basin implies that at least its later evolution was influenced by rifting between Antarctica and India/Sri Lanka [Stagg, 1985].

Seismic records from Prydz Bay [Stagg, 1985] show an older sequence with seaward dipping (1° – 5°) reflectors and minor, localized deformation (sequence PS 5, Figure 5). This sequence is overlain by several undeformed sequences of sigmoid-oblique reflectors (sequences PS 4 through PS 2). A major unconformity separates these older sequences from a younger draping

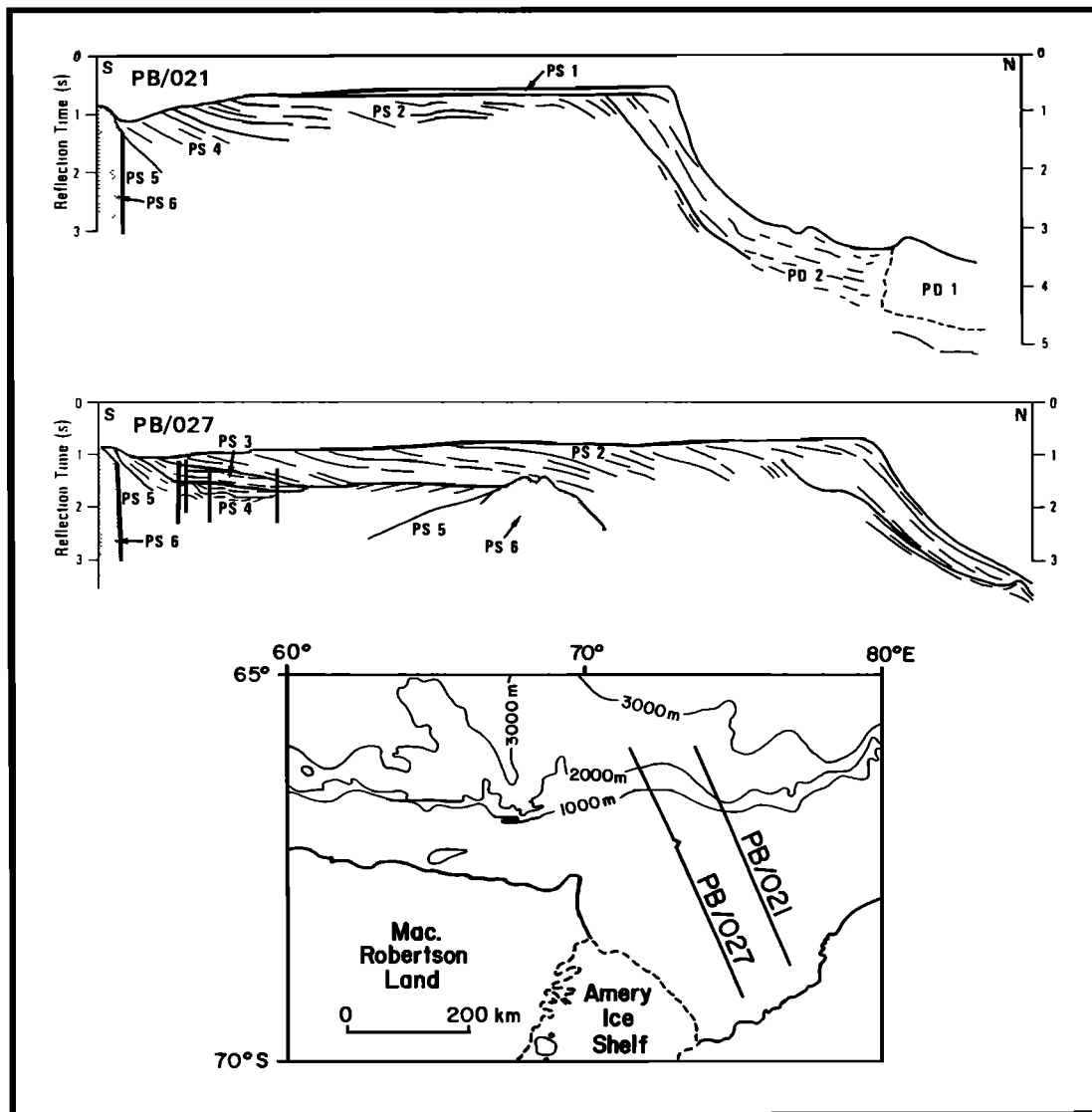


Fig. 5. Interpreted seismic reflection profiles from Prydz Bay [from Stagg, 1985].

sequence (sequence PS 1) that is up to 200 m thick and is inferred to consist of glacial-marine deposits [Stagg, 1985]. The older sequences subcrop on the inner shelf where later episodes of glacial erosion have cut deeply into them.

Stagg [1985] suggests that the oldest deposits of the Prydz Bay Basin are Permo-Triassic sedimentary rocks similar to deposits that crop out along the sides of Lambert Glacier. These deposits show broad parallels to sequences of the intracratonic Gondwana basins of peninsular India (R. Tingey, personal communication, 1988).

During ODP Leg 119, four sites were drilled on the continental shelf in Prydz Bay (sites 739–742), and one

site was drilled on the adjacent continental slope (site 743). Figure 6 shows the locations of these sites, the lithologies and ages of units, and the interpreted environments of deposition for these units. These sites were drilled in the vicinity of seismic reflection line PB 021 (Figure 5). Site 740 penetrated through the younger glacial deposits and into fluvial/floodplain deposits of unknown age. Site 741 penetrated a carbonaceous unit below the glacial sequence which has been tentatively assigned an Eocene age [Barron *et al.*, 1989]. The oldest sediments penetrated at site 742 consist of interbedded diamictons, sandstones, and mudstones which are interpreted as fluvial/lacustrine and glacial deposits and are of probable Eocene age [Barron *et al.*, 1989]. These

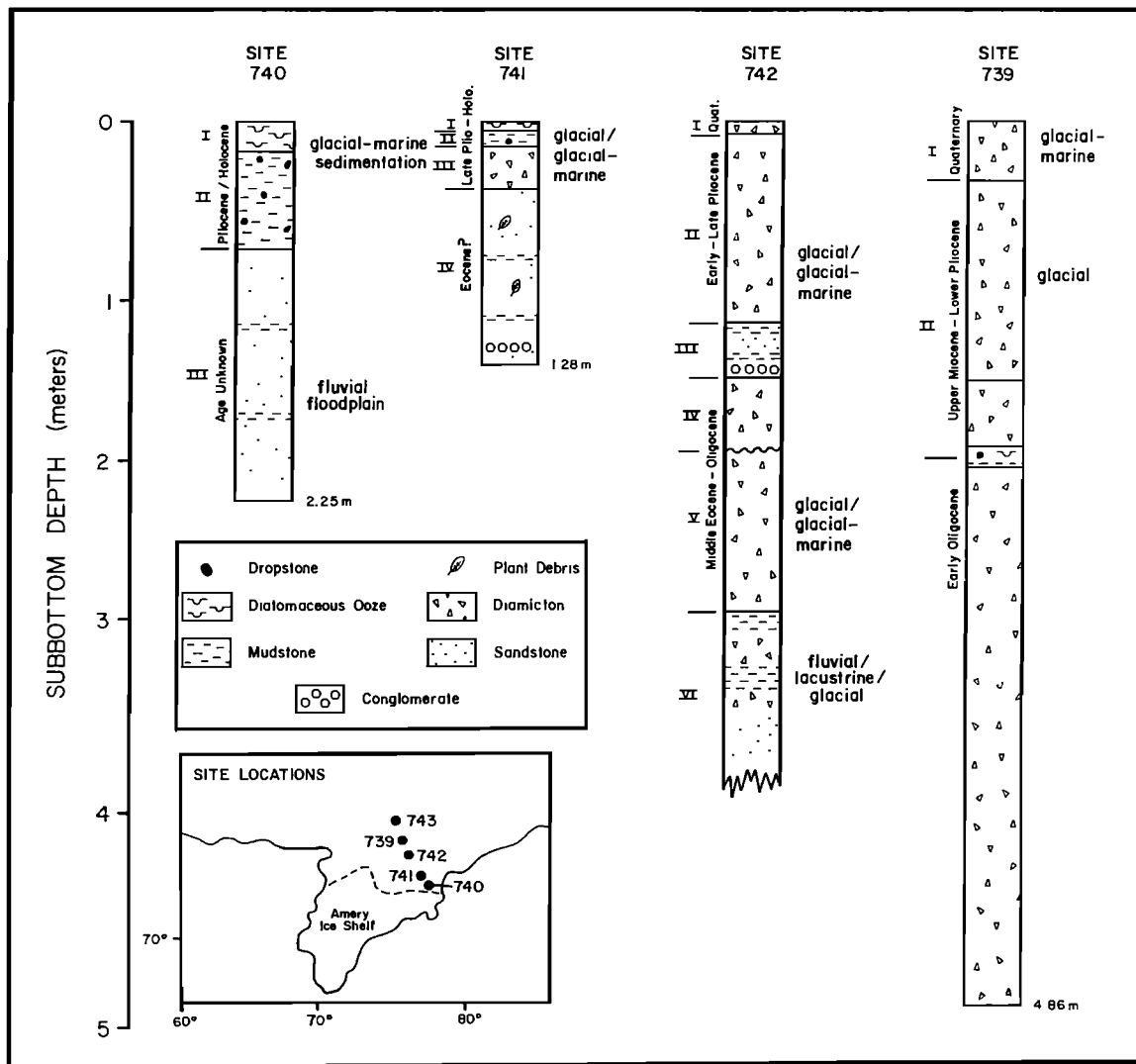


Fig. 6. Lithologic logs of ODP Leg 119 sites on the continental shelf [from Barron *et al.*, 1989].

deposits are overlain by glacial and glacial-marine deposits of Pliocene and younger age. The glacial sequence on the shelf dates back to about middle Eocene age and consists of a thick (486 m at site 739 on the outer shelf) diamictite/diamicton sequence.

Seismic profiles from the Queen Maud Land continental margin [Hinz and Krause, 1982] show a major escarpment, the "Explora Escarpment" of Hinz and Krause, which extends from approximately 10°E to 25°W (Figures 7 and 8). The continental shelf in this sector of the Weddell Sea is less than 70 km wide, which is much narrower than the remainder of the Weddell Sea shelf, and the continental slope is quite steep (up to 40°). These features favor shearing along the margin, as predicted in the Lawver *et al.* [1985] reconstruction. The conjugate margin is the Mozambique Escarpment.

Seismic profiles from the Queen Maud Land margin show a consolidated lower sequence of oceanward dipping reflectors which Hinz and Krause term the "Explora Wedge" (Figure 8). An extensive unconformity, the "Weddell Sea Unconformity" [Hinz and Krause, 1982], separates this lower sequence from several draping sequences (Figure 8). Hinz and Krause's interpretation of these sequences is that the Weddell Sea Unconformity is a late-middle Jurassic feature, associated with continental breakup, and the Explora Wedge is interpreted as consisting of volcanic deposits of the early rifting stage.

During ODP Leg 113, three sites (sites 691, 692, and 693) were drilled on the midslope bench of the Queen Maud Land margin in the vicinity of the Explora Escarpment. Site 691 was drilled in a deep submarine

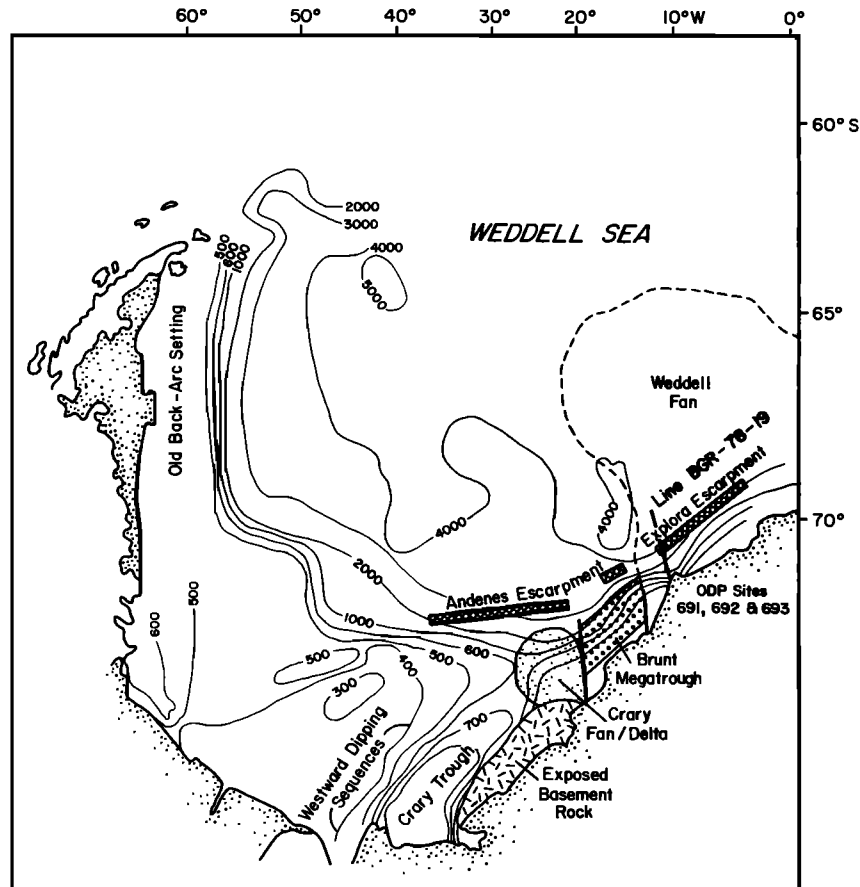


Fig. 7. Significant geological features of the Weddell Sea.

canyon (Wegener Canyon) and was aborted owing to the presence of coarse, unconsolidated material. Site 692 penetrated early Cretaceous (Aptian to Albian?) nanofossil claystone with organic carbon content averaging 8.6% [Barker *et al.*, 1988]. Shipboard analysis of these claystones indicates a strong resemblance to similar age deposits of the Falkland Plateau and deposition in water depths of 500 to 1000 m and under weakly

aerobic conditions [Barker *et al.*, 1988]. These deposits are situated approximately 1200 m above the Explora Wedge. The Cretaceous deposits are overlain by gravels of unknown age, probably canyon deposits, and Miocene to Pleistocene mud.

Site 693 penetrated 398 m of Pleistocene to lower Oligocene hemipelagic muds resting unconformably on early Cretaceous claystone, mudstone, diatomite, and

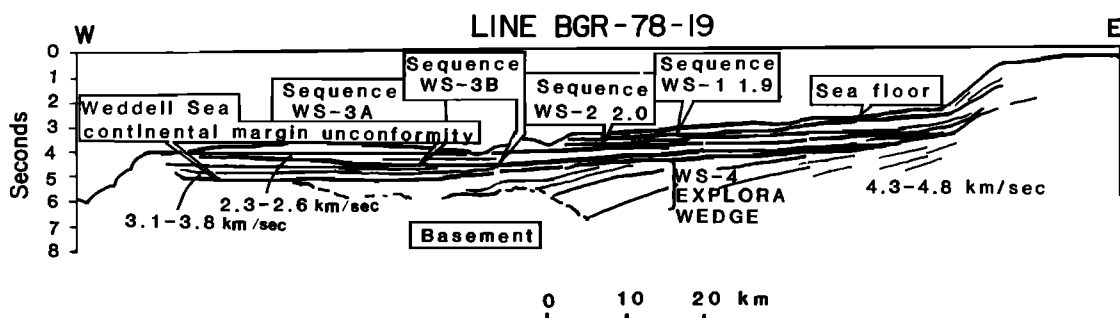


Fig. 8. Interpreted seismic reflection profile BGR-78-19 from the Weddell Sea sector of the Queen Maud Land margin [from Hinz and Krause, 1982]. (See Figure 7 for profile location.)

silicified sandstone [Barker *et al.*, 1988]. The results of shipboard analyses indicate that the early Cretaceous mudstones are the oxidized equivalents of the Aptian mudstones recovered at site 692.

Data acquired at five sonobuoy stations on the Queen Maud Land continental shelf [Hinz and Krause, 1982] indicate that between 4 and 6 km of sedimentary deposits occur there. Seismic reflection records from this portion of the continental shelf show prograding clinoform sequences with toplap termination by either a thin sediment veneer and/or the present seafloor [Hinz and Krause, 1982].

The only information concerning the probable age of the deposits which underlay the continental shelf comes from reworked palynomorphs from Quaternary glacial and glacial-marine sediments. These deposits contain assemblages dominated by marine dinoflagellates, as well as subordinate spores and pollen which indicate an origin in mostly marine deposits of Aptian through Cenomanian age [Truswell and Anderson, 1985]. These same deposits contain abundant sedimentary rock clasts which include quartz arenites [Anderson *et al.*, 1990a].

The modern deep-sea setting of Queen Maud Land is dominated by the Weddell Fan (Figure 7), which is one of the largest submarine fans in the world [Anderson *et al.*, 1986]. A number of piston cores from the fan have penetrated sands that consist dominantly of quartz, implying that a quartz-rich source is situated somewhere in Queen Maud Land, probably on the continental shelf [Anderson *et al.*, 1986]. Diatoms from ODP site 692 date the canyon cutting at this site as early late Miocene or older.

Hydrocarbon Potential

Several kilometers of sedimentary deposits occur on the outer continental shelf in Prydz Bay, and carbonaceous sediments were penetrated there at ODP site 741 [Barron *et al.*, 1989], although there is doubt as to whether these deposits are buried deep enough to have experienced thermal maturation. Potential reservoir sands, including the fluvial sandstones penetrated at sites 740, 741, and 742 (Figure 6), are apparently widespread on the shelf.

Sediment thicknesses on the Queen Maud Land margin are 4–6 km [Hinz and Krause, 1982], but these deposits are mainly situated above the oil generation window calculated by Hinz and Block [1983] of 5.5 to 7.5 km. This implies that only the deposits of the Explora Wedge are buried sufficiently deep to have generated hydrocarbons. However, it is important to recognize that heat flow data for the region are scarce; so Hinz and Block's calculations must be taken as preliminary.

Potential source rocks of the Queen Maud Land margin include the early Cretaceous carbonaceous mud-

stone drilled during ODP Leg 113 at sites 692 and 693 [Barker *et al.*, 1988]. These deposits are situated above the oil generation window of Hinz and Block [1983]. Potential reservoir rocks may exist in the area of the Weddell Fan and on the adjacent shelf. Quartz sands and sandstone clasts are abundant in Quaternary glacial sediments on the shelf [Anderson *et al.*, 1990a] and in turbidites of the Weddell Fan [Anderson *et al.*, 1986].

WEDDELL SEA SECTOR

Geology

The exact timing and kinematics of the development of the Weddell Sea remain problematic, owing largely to an insufficient geophysical data base from the region and to the complex and poorly understood prebreakup history of the South Atlantic region. One of the most recent attempts at resolving the prebreakup history is that of Lawver *et al.* [1985]. According to this model the Weddell Sea formed principally as a passive ocean basin south of a major spreading center between east and west Gondwana (Figure 9), with initial seafloor spreading commencing by the late Jurassic [LaBrecque and Barker, 1981].

By 130 Ma, spreading had commenced between Africa and South America [Lawver *et al.*, 1985]. A triple junction was present in the South Atlantic north of the Weddell Sea, with the southeastern arm of that triple junction extending to the Queen Maud Land margin (Figure 9). At 80 Ma this feature underwent a change from a ridge-ridge-ridge triple junction to a ridge-fault-fault triple junction [Lawver *et al.*, 1985]. Coincident with this change in the configuration of the triple junction, southward motion of Antarctica ceased and the continent began a clockwise rotation with respect to South America. The western Weddell Sea margin experienced passive margin conditions as the two continents drifted apart.

The earliest seismic surveys of the eastern Weddell Sea were conducted during the 1976–1977 austral summer by scientists from the Norwegian Polar Institute [Fossum *et al.*, 1982; Haugland, 1982; Haugland *et al.*, 1985; Kristoffersen and Haugland, 1986]. Later surveys were conducted by scientists from the United States [Gordon and LaBrecque, 1977; LaBrecque *et al.*, 1980], West Germany [Hinz and Krause, 1982; Hinz and Block, 1983; Miller *et al.*, 1984], Japan [Okuda *et al.*, 1983], the USSR [Grikurov, 1980; Kamenev and Ivanov, 1983], and Argentina [Keller *et al.*, 1985].

Kristoffersen and Haugland [1986] examined multi-channel seismic reflection data acquired during the 1984–1985 Norwegian Antarctic Research Expedition to the southeastern Weddell Sea. They mapped an escarpment ("Andenes Escarpment"), which they argue is a continuation of the Explora Escarpment, some 700 km farther south to about 40°W (Figure 7). Kristoffersen

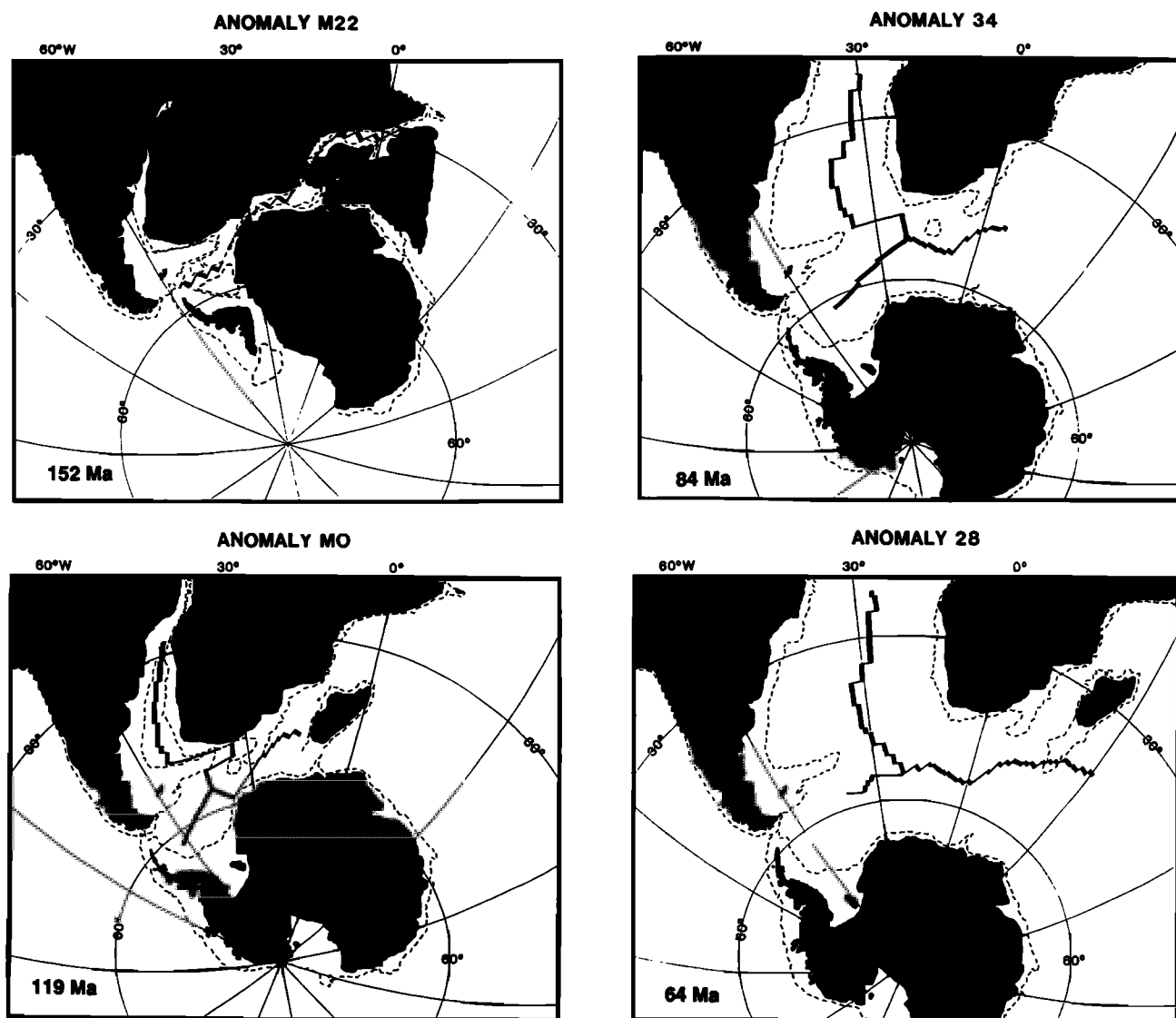


Fig. 9. Lawver *et al.*'s [1985] model for the opening of the Weddell Sea.

and Haugland argue that differences in seafloor magnetic anomalies and seismic reflection character on either side of the escarpment indicate that this feature is an ancient Gondwana plate boundary separating oceanic crust to the north from crust of unknown origin to the south. They further argue that the available data indicate that the Andenes-Explora escarpments are structures of a rifted margin, or possibly a plate boundary related to oblique spreading, rather than a sheared margin. Lawver and Scotese [1987] counter this argument by suggesting that the Andenes Escarpment is associated with a younger rifting event (~130 Ma to present) and is only coincidentally in line with the Explora Escarpment.

Haugland [1982] describes the continental shelf of the southeastern Weddell Sea as a "typical prograding continental shelf with no major tectonic activity" [Haugland, 1982, p. 409]. Sonobuoy data show sediment thicknesses of 2.0 to 2.5 km [Haugland, 1982], except in the area between approximately 73°S and 75°S. Here, a narrow, deep basin with over 10 km of sediment has been mapped by Kamenev and Ivanov [1983]. They call this basin the Brunt Megatrough (Figure 7).

Sparker profiles collected from the continental shelf north of Brunt Megatrough were examined in detail and a seismic stratigraphy for this part of the shelf developed from these data by Roqueplo [1982]. She recognized a basal sequence which drapes acoustic basement

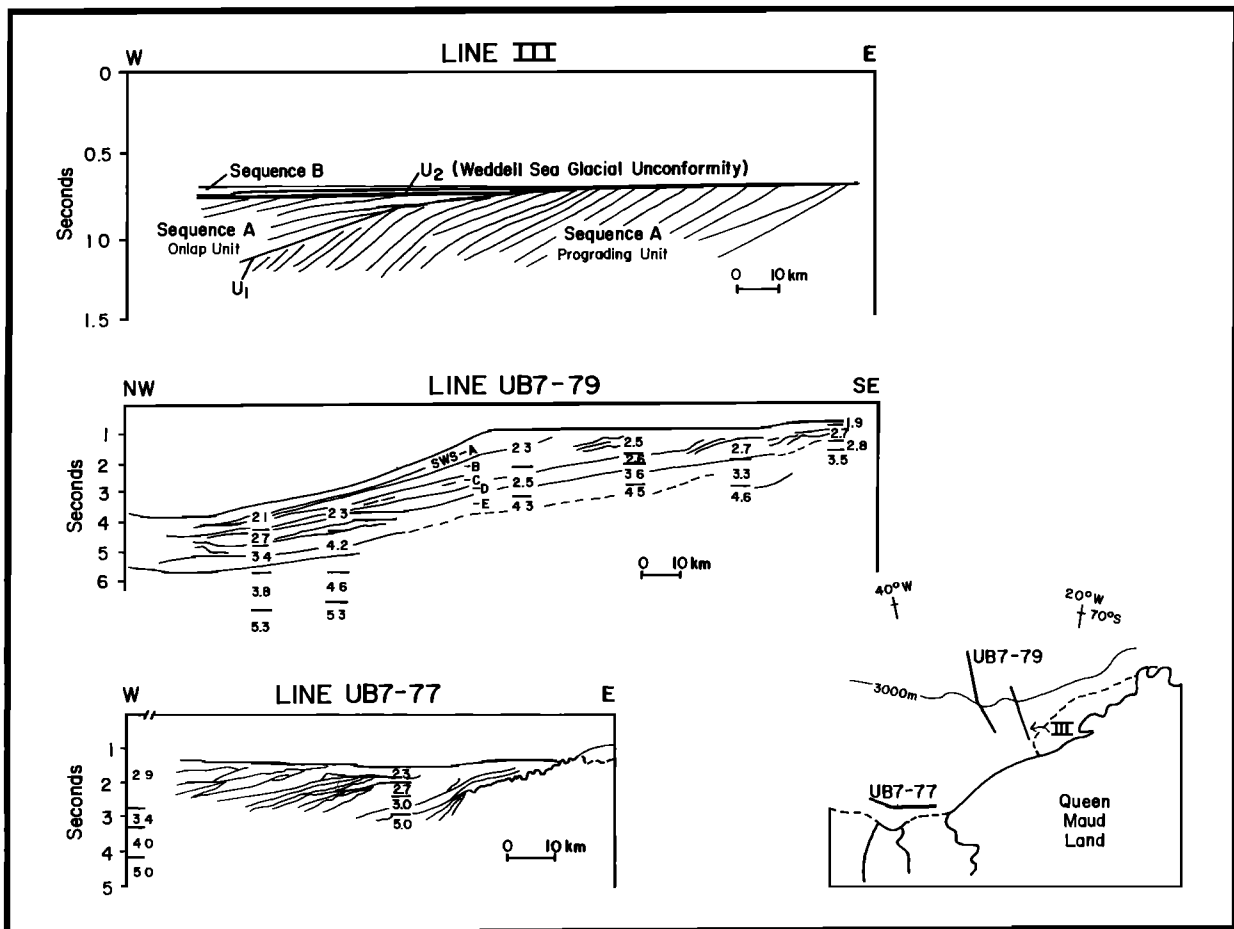


Fig. 10. Interpreted seismic reflection profiles from the eastern Weddell Sea. Line III is from Roqueplo [1982] (data provided courtesy of George Maisey), and lines UB7-79 and UB7-77 are from Haugland *et al.* [1985]. Seismic velocities (in kilometers per second) are provided for lines UB7-79 and UB7-77.

and dips seaward at 1° to 2° that is more than 500 m thick. This draping unit is overlain by a relatively thick (approximately 900 m) prograding sequence with 2° to 3° seaward dips, which displays a broad lobate pattern (Figure 10, line III). On the outer shelf this sequence is overlain, in onlap fashion, by another sequence (Figure 10). The prograding unit has been deeply eroded and is unconformably overlain by a relatively thin sequence of supposed glacial and glacial-marine origin. This unconformity appears to be widespread on the shelf and is referred to as the Weddell Sea Glacial Unconformity (Figure 10).

Seismic records were collected from the vicinity of Brunt Megatrough during the Norwegian Antarctic Research Expeditions of 1976–1977 and 1978–1979. These data, in addition to seismic refraction data from the area, indicate sediment thicknesses in excess of 5 km. Seismic reflection records from this portion of the margin show several progradational sequences that

have been eroded by glacial ice [Haugland *et al.*, 1985] (Figure 10). Acoustic velocities of the progradational sequences range from 2.3 to 4.0 km/s. The prominent feature in the area is the Crary Fan (Figure 7). This is a large submarine fan situated at the mouth of Crary Trough, which Haugland *et al.* [1985] believe was formed in Tertiary time. Roqueplo [1982] recognized this same feature from sparker profiles acquired in the area but interpreted it as a shelf edge delta.

South of the Brunt Megatrough, along the Coats Land coast, acoustic basement is exposed on the continental shelf [Roqueplo, 1982; Elverhoi and Maisey, 1983; Haugland *et al.*, 1985] (Figure 7). It has high magnetic susceptibility and is thus interpreted as being of igneous origin [Roqueplo, 1982]. This is an extension of the Transantarctic Mountains.

Crary Trough (Figure 7) is a deep glacial trough eroded by expanded ice streams flowing from both East Antarctica and West Antarctica [Anderson *et al.*,

1990a]. It is typical of other longitudinal troughs of the Antarctic region in that it represents pronounced glacial erosion along the contact between crystalline basement rocks and the overlying sedimentary sequence [Elverhoi and Maisey, 1983; Anderson, 1990]. The trough itself coincides with a large positive gravity anomaly, which is interpreted as either a zone of crustal thinning or an intrusive body [Behrendt, 1962]. Ivanov [1983] calls this feature the "Filchner Glacier Riftogenic Graben" and infers that it extends several hundred kilometers to the south, beneath the Filchner Ice Shelf.

Seismic reflection profiles acquired across the southern part of Crary Trough show a thick westward dipping sequence of reflectors [Elverhoi and Maisey, 1983; Ivanov, 1983; Haugland *et al.*, 1985]. Haugland *et al.* [1985] found that there is little evidence of large tectonic features in the trough. Rather, sedimentary sequences onlap basement (Figure 10, line UB7-77). Two sonobuoy measurements from the trough indicate sediment thicknesses of about 2 km near the axis of the trough and 4.5 km in its western flank [Haugland, 1982]. Seismic velocities range from 2.6 to 4.0 km/s [Haugland, 1982]. The sedimentary sequence that is exposed in the western flank of Crary Trough thickens to the west and approaches 10 km west of the trough [Ivanov, 1983].

Reworked palynomorphs in Quaternary glacial and glacial-marine deposits from the southeastern Weddell Sea continental shelf and Crary Trough consist mainly of Cretaceous nonmarine assemblages, in contrast to the dominantly marine assemblages of the northeastern shelf [Anderson *et al.*, 1990a]. This implies that marine incursions did not occur south of approximately the Brunt Megatrough until after Cretaceous time. Sedimentary clasts from these same sediments include quartz arenite and arkose, and two piston cores from the shelf situated just west of Crary Trough penetrated outcrops of quartz sand of eolian and coastal origin [Anderson, 1990].

The continental shelf of the western Weddell Sea is relatively broad (averaging 300 km in width) and has an average depth of 450 m. Sea ice covers the region throughout the year, so very few shipboard geophysical measurements have been made there. Seismic reflection profiles were collected along the front of the Ronne Ice Shelf and on the continental margin adjacent to the Larsen Ice Shelf during the West German Antarctic II cruise of *Polarstern*, but only preliminary results have been published at this time [Miller *et al.*, 1984]. Inferences about the geology of the continental margin must, therefore, rely heavily on plate reconstructions for the region and on studies from the adjacent Antarctic Peninsula.

The western shelf lies within the extensive back-arc terrain associated with the Palmer Magmatic Arc [Elliot, 1983]. This terrain resulted from the subduction of

Pacific Ocean floor beneath a continental margin during and after the breakup of Gondwana [Thomson *et al.*, 1983]. Nearly 14 km of geosynclinal sediments comprise the Trinity Peninsula Group, which is the pre-Jurassic basement of the magmatic arc. A typical succession of the Trinity Peninsula Group consists of mudstone or shale alternating with beds of siltstone or sandstone.

Large-scale folding of Trinity Peninsula Group rocks prior to Mesozoic time was accompanied by regional metamorphism which increases in grade toward the southwest [Elliot, 1983]. Middle Jurassic alluvial deposits derived from the Trinity Peninsula Group are sparsely distributed over the northern Antarctic Peninsula. A typical sequence consists of conglomerates which fine upward into coarse sandstones and dark plant-bearing mudstones and shales [Elliot and Gracanin, 1983].

Thick post-early Jurassic volcanoclastic deposits of the Latady Formation [Laudon *et al.*, 1983] and its equivalents in the southern Antarctic Peninsula [Rowley and Williams, 1982] outcrop extensively along the entire length of the western Weddell Sea coast. These deposits exceed 800 m in thickness and are comprised mainly of shallow marine siltstone, black mudstone, and shale, with rare sandstone and very thin coal beds. In the northern Antarctic Peninsula, greater than 550 m of radiolarian-rich black mudstone and tuffs of the Jurassic Nordenskjöld Formation accumulated along the margin of a euxinic back-arc basin [Farquharson, 1983]. These sedimentary deposits are overlain by the Upper Jurassic Volcanic Group, which is comprised of agglomerates, rhyolites, and andesites. These volcanic rocks mark the inception of volcanism associated with the active plate margin [Elliot and Gracanin, 1983]. By early Cretaceous time, continued uplift led to the emergence of a magmatic arc at the site of the present peninsula [Farquharson, 1983].

Late Mesozoic to early Cenozoic sedimentary rocks that outcrop on James Ross Island and Vega Island represent marine volcanoclastic sediments deposited in a broad back-arc basin that developed on the eastern border of the Trinity Peninsula [del Valle *et al.*, 1982]. Nearly 4.5 km of sediments accumulated in a basin adjacent to the rising landmass during the Andean Orogeny.

Late Cretaceous sedimentary rocks of the Marambio Group occur within the James Ross Island basin, with exposures on James Ross Island and Seymour Island. Deposition of the Marambio Group occurred in response to the steady uplift of the Antarctic Peninsula and northwestward migration of the magmatic arc [Elliot, 1983]. The total thickness of this group exceeds 4.5 km. It consists of marine conglomerates and calcareous, often glauconitic, sandstones that were deposited in a shallow marine environment [Rinaldi, 1982]. Further to the east, in the area of the present continental margin, a

large submarine fan system may have existed. This fan was perhaps similar to that which occurs in similar age deposits of the Magallanes Basin of South America [Dott *et al.*, 1982].

Lower Tertiary strata are also exposed on Seymour Island and include the Paleocene Cross Valley Formation and the late Eocene to early Oligocene La Meseta Formation. The Cross Valley Formation consists of sandstones and carbonaceous silt and silty sand deposited in deltaic environments. The La Meseta Formation consists of silty sands, sands, and clays of prodelta, lagoonal, and deltaic origin [Elliot and Trautman, 1982]. These sedimentary deposits are capped by the Pliocene James Ross Island Volcanic Group.

The sequence of deposits described above is believed to underlie the continental shelf of the western Weddell Sea.

Hydrocarbon Potential

Two areas of the Weddell Sea Sector have good potential for oil and gas reserves: the Brunt Megatrough/Crary Fan and the continental shelf situated west of Crary Trough. Both areas have thick sedimentary sequences, and drill sites from the nearby deep-sea floor (Leg 113 sites) penetrated potential source rocks (Cretaceous carbonaceous mudstones). Good reservoir rocks and cap rocks may occur within the large delta/fan systems of the region.

Hydrocarbon potential is considered high in the western Weddell Sea as potential source rocks and reservoir rocks are known to occur in the region. The total thickness of sedimentary deposits on the continental margin is unknown, but judging from the thick sequences that are exposed on Seymour Island and James Ross Island, thicknesses on the continental margin must be of the order of several kilometers. Furthermore, the geothermal history of the region is thought to have been conducive to oil and gas generation at relatively shallow depths.

ROSS SEA/MARIE BYRD LAND SECTOR

Geology

The Ross Sea is the most thoroughly studied portion of the Antarctic continental shelf. The earliest geophysical surveys of the Ross Sea were conducted during cruises 27, 32, and 52 of the United States research vessel *Eltanin* and included single-channel seismic reflection (sparker), seismic refraction, gravity, and magnetic surveys [Houtz and Meijer, 1970; Houtz and Davey, 1973; Hayes and Davey, 1975]. More recently, multichannel seismic reflection surveys have been conducted by West German [Hinz and Block, 1983], Japanese [Sato *et al.*, 1984], Soviet, Italian, and U.S. [Cooper *et al.*, 1987, 1988a, b, 1990] scientists. How-

ever, to date only the U.S. data have been made public and described in any detail [Cooper *et al.*, 1987]. No geophysical surveys have been conducted on the Marie Byrd Land continental margin.

Prior to the breakup of Gondwana, the area of the present Ross Sea and Marie Byrd Land was connected to the New Zealand microcontinent (Figures 2 and 11), which included the present Campbell Plateau and the South Tasman Rise [Barron *et al.*, 1989; Jago, 1984]. During the latest Paleozoic and throughout the Triassic, the area of the present Ross Sea was a broad continental platform over which an extensive blanket of alluvial deposits, the Beacon Supergroup, was shed [Barrett, 1981]. Initial rifting began in the early Jurassic (175 Ma), and tholeiitic mafic rocks (Ferrar Dolerite and Kirkpatrick Basalt) were extruded and intruded over large areas. Crustal extension during the early rift period resulted in the development of rift grabens trending parallel (NNE-SSW) to the axis of spreading (Figure 11). The New Zealand microcontinent remained fixed to Gondwana until around 80 Ma [Christoffel and Falconer, 1972; Molnar *et al.*, 1975; Davey, 1981]. During breakup, which spans most of Cretaceous time, nonmarine and shallow marine clastic sediments were shed into rift basins, probably in association with layered volcanic rocks.

Cooper *et al.* [1988a] emphasize that the evolution of the Ross Sea continental shelf and its sedimentary basins was strongly influenced by a second, Cenozoic (post-Eocene?) stage of rifting. This later rifting event was associated with a major episode of plate reorganization during the Eocene [Molnar *et al.*, 1975; Stock and Molnar, 1987; Cande and Mutter, 1982] and with uplift of the Transantarctic Mountains, volcanism in Victoria Land and Marie Byrd Land, and gentle regional subsidence of Ross Sea depocenters [Cooper *et al.*, 1988a].

Four sedimentary basins have been identified in the Ross Sea region: the Eastern Basin, Central Trough, Victoria Basin, and Byrd Basin (Figure 12). All are elongate basins with their long axes oriented NNE-SSE, and all four basins are associated with rift grabens [Cooper *et al.*, 1988a]. The Byrd Basin is situated entirely beneath the Ross Ice Shelf, and so its geology is poorly known. The other three basins are situated on the open shelf, although they may extend at least 1000 km beneath the Ross Ice Shelf.

The Eastern Basin is located on the outer shelf of the eastern Ross Sea (Figure 12). It is the only one of the outer shelf basins that is not situated entirely within an early rift graben [Cooper *et al.*, 1988a]. The total sedimentary section within the basin is up to 6-7 km thick within the area of the early rift graben [Davey *et al.*, 1982; Cooper *et al.*, 1988a]. Seismic reflection profiles from the basin (Figure 13) show several prograding sequences (RS-6 through RS-3), each separated

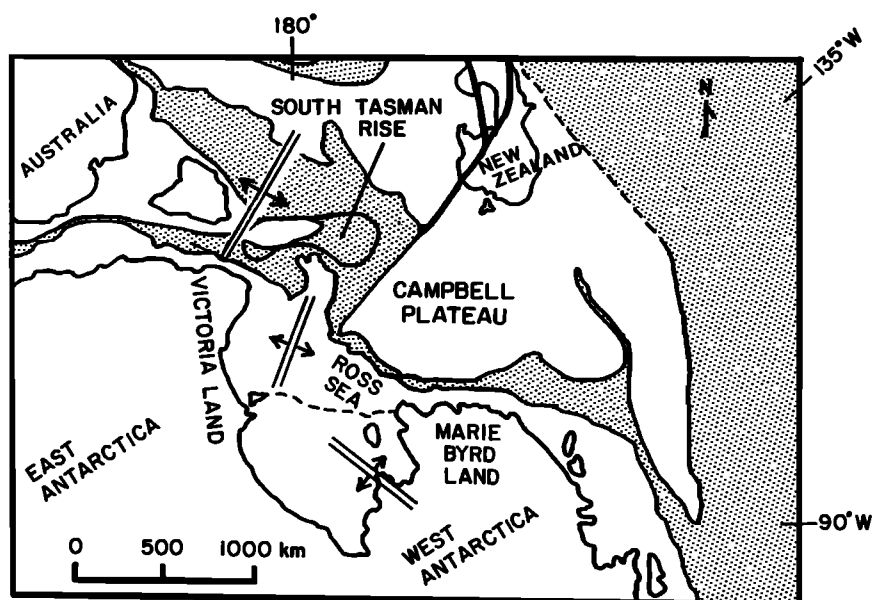


Fig. 11. Reconstruction of the Ross Sea region at 80 Ma (compiled from information by *Barron and Harrison* [1979], *Jago* [1984], *Weissel et al.* [1977], and *Davey* [1981]). Northeast-southwest oriented spreading centers are believed to have been active about 55 Ma [Weissel et al., 1977]. Spreading in the eastern Ross Sea may have occurred along a more east-west oriented spreading center between 100 and 20 Ma [Davey, 1981].

by an unconformity [Hinz and Block, 1983]. Hinz and Block [1983] and Sato et al. [1984] suggest that these strata were deposited in fluvial deltas because they display oblique, sigmoid, and complex sigmoid seismic reflectors. Younger draping sequences (RS-1 and RS-2) are supposedly glacial-marine in origin.

Three Deep-Sea Drilling Project (DSDP) Leg 28 sites (270, 271, and 272) were drilled along the southwestern edge of the Eastern Basin (Figure 12). The total composite sedimentary section drilled at all three sites was about 1200 m thick; so only the upper (glacial-marine) portion of the basin fill was penetrated. The oldest sediments drilled include shallow marine glauconitic sands and sedimentary breccias of late Oligocene (25–26 Ma) age, based on K/Ar dates derived from glauconites. These deposits rest on continental basement rocks [Hayes and Frakes, 1975]. The sampled interval consists mainly of poorly sorted glacial-marine deposits [Barrett, 1975; Hayes and Frakes, 1975]. The upper section is characterized by a widespread glacial erosional surface, which is capped by a thin sequence consisting of glacial and glacial-marine deposits.

The Central Trough coincides approximately with a prominent north-south oriented positive gravity anomaly, which Hayes and Davey [1975] believe marks the approximate position of a short-lived spreading center (Figures 11 and 12) and associated high-density intrusive rocks. The eastern margin of the Central Trough probably coincides with a major transform, separating the north-south oriented rift from an east-west oriented spreading center (Figure 11) in the eastern Ross Sea

[Davey, 1981]. The proposed transform is in alignment with the Campbell Fault to the north, along which 300 to 330 km of dextral offset has occurred [Davey and Christoffel, 1978].

The Central Trough contains up to 6–7 km of virtually undeformed sedimentary deposits [Hinz and Block, 1983; Cooper et al., 1988a]. The sequence stratigraphy of the trough is similar to that of the Eastern Basin. The rift basin fill sequence probably consists mainly of Cretaceous-early Paleogene continental and shallow marine deposits. It is separated from the overlying glacial-marine sequence (post-late Oligocene) by a prominent unconformity which is probably Eocene to Oligocene in age [Cooper et al., 1988a].

The Victoria Land Basin is situated in the western Ross Sea, adjacent to the Transantarctic Mountains, and extends from the mid-shelf to perhaps several hundred kilometers beneath the Ross Ice Shelf [Cooper et al., 1988a, 1990]. It is a structurally complex basin, actually consisting of a number of subbasins and grabens, and is associated with a zone of crustal thinning [Davey et al., 1982]. Large basement faults associated with the early rifting phase do not offset the overlying rift basin fill sequence. However, younger strata of the westernmost portion of the basin are offset by normal faults which extend from the basement to the seafloor and are associated with uplift of the Transantarctic Mountains [Cooper et al., 1988a], which took place during the late Cenozoic. Between 2 and 5 km of sedimentary deposits occur within the Victoria Land Basin [Eittreim and Cooper, 1984].

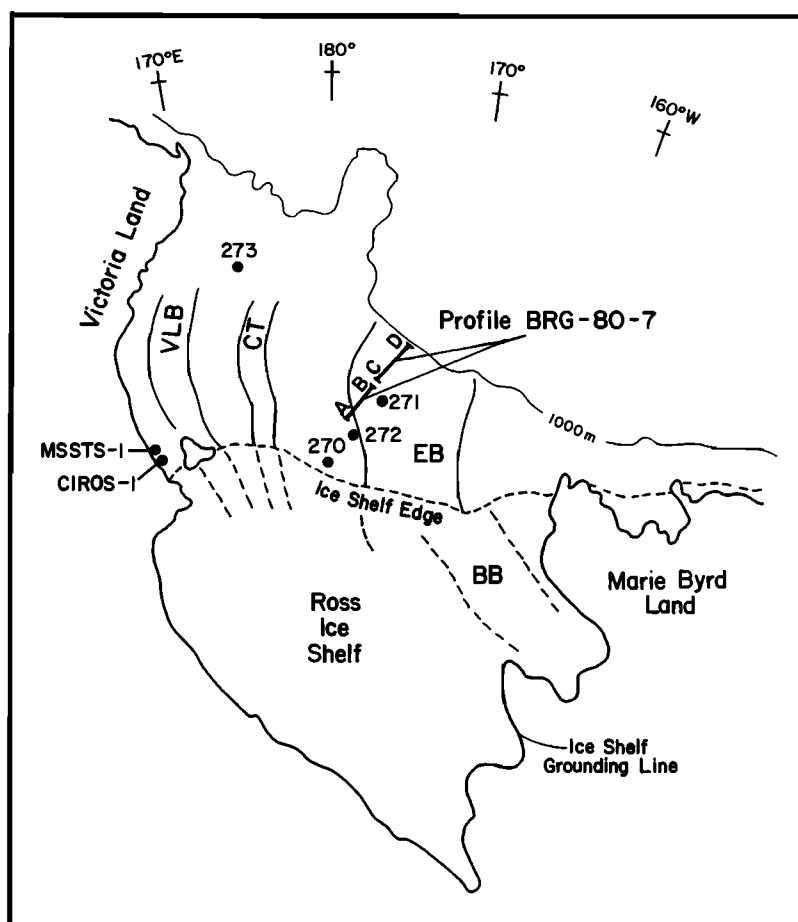


Fig. 12. Sedimentary basins of the Ross Sea and the location of DSDP, MSSTS, and CIROS drill sites. Also shown is the location of seismic profile BRG-80-7, shown in Figure 13. BB, Byrd Basin; EB, Eastern Basin; CT, Central Trough; and VLB, Victoria Land Basin.

The Byrd Basin is situated beneath the Ross Ice Shelf, and its presence is inferred from seismic refraction data [Bentley and Ostenso, 1961] and aeromagnetic data [Bentley and Clough, 1972] which indicate that about 2 km of sedimentary deposits occur in this basin. Truswell [1983] and Truswell and Drewry [1984] suggest that abundant recycled palynomorphs of late Cretaceous through Tertiary age that are found in Quaternary glacial and glacial-marine sediments on the Ross Sea continental shelf were derived from the Byrd Basin.

Hydrocarbon Potential

Evaluations of the hydrocarbon potential of the Ross Sea have been made by Wright and Williams [1974], Cameron [1981], Behrendt [1983, this volume], Hinz and Block [1983], Lock [1983], Cook [1983], Cook and Davey [1984], Davey [1985], St. John [1986], and Cooper *et al.* [1988b]. Cooper *et al.* [1988b] provide a detailed and current evaluation; so only a brief review of

the area's hydrocarbon prospectiveness is provided in this paper.

Cook [1983] used the thermal maturation mode of Waples [1980] and a single heat flow measurement of 50–70 mW/m² from Roosevelt Island [Thomas *et al.*, 1980] to estimate the level of the oil generation window. His model predicts that basins of the Ross Sea may have reached the onset of oil generation sometime between 17 and 26 Ma and that the depth of the oil generation window is likely situated between 2.8- and 4.0-km depth. These results are consistent with those of Cooper *et al.* [1988b], but the oil window is up to 1600 m shallower than was calculated by Hinz and Block [1983] and Cook and Davey [1984], owing to differences in assumed heat flow values. Heat flow measurements [Blackman *et al.*, 1987] and evolutionary rift models for the Ross Sea indicate that above normal subsurface temperatures have existed there since Mesozoic time [Cooper *et al.*, 1988b]. Since the Ross Sea sedimentary

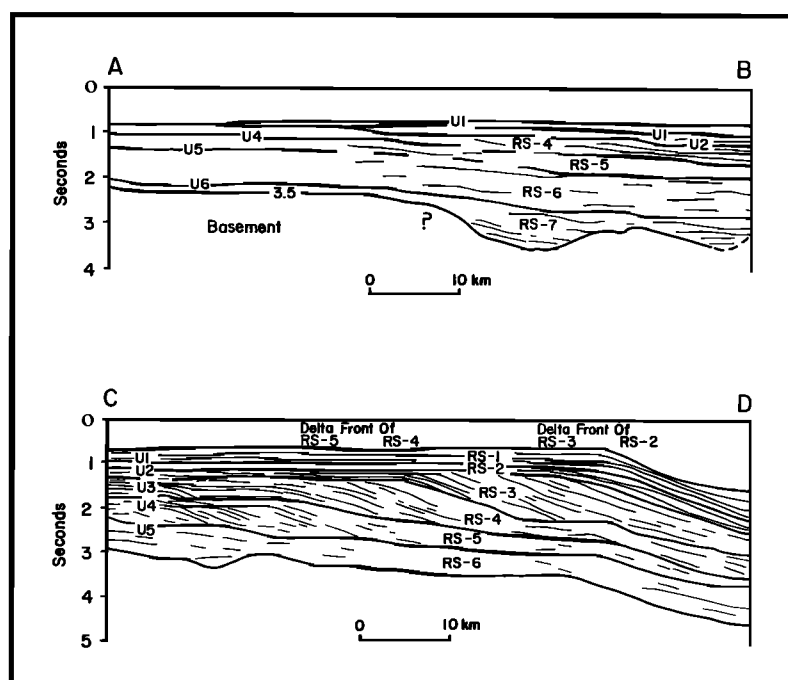


Fig. 13. Interpreted seismic reflection profile BRG-80-7 from the Ross Sea continental shelf [from *Hinz and Block*, 1983]. (See Figure 12 for location of profile.)

basins each contain more than 8 km of sedimentary deposits [Cooper *et al.*, 1988b], there may well be hydrocarbons within these basins.

Potential source rocks in the Ross Sea will most likely be of Cretaceous-early Paleogene age, as younger deposits are mainly situated above the predicted oil window. Sedimentary deposits of this age are not exposed in the Ross Sea region; however, Cretaceous deposits of nonmarine and shallow marine origin do occur in contiguous basins of the Campbell Plateau [Anderson *et al.*, 1982] and in basins along the western margin of Tasmania [Hinz *et al.*, 1986]. Furthermore, recycled late Cretaceous and Paleogene marine microfossils occur in the Sirius Formation [Webb *et al.*, 1984], which is exposed in the Transantarctic Mountains, and recycled palynomorphs of this age occur in Quaternary glacial deposits of the Ross Sea [Truswell, 1983; Truswell and Drewry, 1984].

Direct evidence of hydrocarbons in the Ross Sea comes from the CIROS-1 drill site in McMurdo Sound (Figure 12). Geochemical analysis [Cook and Woolhouse, 1989] of an asphaltic layer penetrated at this site [Barrett, 1988] indicated that this is a residual deposit from petroleum that has since migrated away from the site. Gas hydrates were also encountered at this site [Barrett, 1988]. Earlier reports of high canned hydrocarbon values in DSDP samples from the Leg 28 sites [McIver, 1975] have been discounted, such values most

likely being the product of localized maturation [Cook, 1983].

Reservoir rocks may be present in both the preglacial and glacial marine sequences of the Ross Sea, but older rift basin deposits are considered poor quality reservoirs, particularly volcanoclastic deposits, owing to diagenetic reduction in porosity [Cooper *et al.*, 1988b].

The most suitable reservoirs likely occur within the late preglacial-early glacial section. During the Paleogene, temperate glaciers bordered the Ross Sea, and there likely were extensive deltas all along the inner shelf, deltas that were nourished with sediment delivered to the sea by rivers draining ancestral mountain ranges of Victoria Land. The continental shelf was much shallower then, and extensive shelf sand bodies may have been formed during sea level low stands. Direct evidence that such sand bodies exist comes from DSDP, CIROS, and MSSTS drill sites. Late Oligocene shallow marine sandstone was penetrated at DSDP site 270 in the central Ross Sea and provides evidence that conditions suitable for sand body formation existed at this time, even on the most remote portions of the shelf. Upper Oligocene muddy sandstones were penetrated at MSSTS-1 which yielded porosities of 17–36% [Collen and Froggatt, 1986]. At CIROS-1, relatively thick sand bodies occur within the Oligocene section [Robinson *et al.*, 1987].

During the late stages of glaciation, ice sheets eroded

the continental shelf by several hundred meters [Houtz and Davey, 1973] and fluvial runoff ceased as polar conditions were established. Since this time, most of the continental shelf has become unsuited for the formation of coastal, deltaic, and shelf sand bodies. Terrigenous sand bodies of Miocene and younger age will likely be confined to the innermost portions of the shelf along the foot of the Transantarctic Mountains. These will be relatively small deltas and fans shed onto the seafloor during interglacials. Miocene and Pliocene sandstones were recovered at MSSTS-1 and yielded porosities of up to 45% [Collen and Froggatt, 1986]. The only other potential reservoirs produced after polar glacial conditions were established are bioclastic carbonates that are being deposited on banks in the western Ross Sea and which occur in small fans at the base of the continental slope [Anderson *et al.*, 1979, 1984]. Piston cores have penetrated up to 4 m of this material on the continental slope [Anderson *et al.*, 1979].

Cooper *et al.* [1988b] believe that stratigraphic traps play a more important role than structural traps in concentrating oil and gas in the Ross Sea. The main exception to this is the Victoria Basin, where structural traps associated with late stage rifting may occur.

ANTARCTIC PENINSULA SECTOR

Geology

One of the major problems in the reconstruction of Gondwana has to do with an apparent overlap between the Antarctic Peninsula and the Falkland Plateau [Dalziel and Elliot, 1982; Lawver *et al.*, 1985; Dalziel *et al.*, 1987]. Figure 1 shows this overlap. Lawver and Scotese [1987] argue that the most reasonable solution to this problem involves a clockwise rotation of the peninsula relative to East Antarctica during the early stages of breakup, since the overlap problem disappears by 118 Ma. This scenario is supported by paleomagnetic data from the Ellsworth Mountains, the Antarctic Peninsula, and Thurston Island [Grunow *et al.*, 1987].

The tectonic evolution of the Antarctic Peninsula sector of the continental margin has been influenced by a series of ridge-trench collisions between the Pacific plate and the Antarctic plate and involving the Aluk Ridge. Ridge-trench collisions occurred progressively northeastward along the margin, subduction taking place episodically between major fracture zones (Figure 14). Initially, the fracture fabric of the subducted plate was oblique to the direction of subduction; however, during the late Cretaceous the Antarctic Peninsula began to subduct seafloor with fracture zones trending parallel to the direction of subduction. Thus the boundaries between segments of different age seafloor stayed at the same point on the margin, allowing tectonic segmentation of the margin [Hawkes, 1981; Barker *et al.*, 1988; Jeffers *et al.*, 1990]. As the ridge was sub-

ducted, spreading and subduction stopped and that segment of the margin became passive. Southwest of the Tula Fracture Zone (Figure 14) the ridge was subducted in the middle to late Eocene [Kimura, 1982], the ridge segment between the Tula and Adelaide fracture zones was subducted in the late Oligocene, the ridge segment between the Adelaide and Anvers fracture zones was subducted in the early Miocene, and the segment between the Anvers and Hero fracture zones was subducted during the late Miocene. The segment north of the Hero Fracture Zone, the Bransfield Segment, is the sole surviving segment of the spreading ridge and associated trench.

No drilling has been conducted on the continental shelf of the Antarctic Peninsula; so the geology there must be inferred from outcrop information from islands of the peninsula region. Throughout the Mesozoic and into the early part of the Tertiary, subduction and associated magmatic activity were occurring all along the margin, and volcanoclastic deposits were shed into marginal basins. These deposits would be correlative to the Jurassic Nordenskjöld and Latady formations, both of which contain carbonaceous intervals. During Cretaceous through Paleocene time, the Antarctic Peninsula was covered by forest with lush undercover. Deposits of this age are exposed on Seymour Island and James Ross Island and include the Marambio Group (late Campanian to possibly earliest Tertiary) and Cross Valley Formation (Paleocene). The Marambio Group has a total thickness of just over 1200 m and includes sandstones, siltstones, and mudstones which include carbonaceous intervals [Elliot and Trautman, 1982; Zinsmeister, 1982]. The Cross Valley Formation consists largely of nonmarine sandstones and volcanoclastic deposits with carbonaceous intervals [Zinsmeister, 1982]. The Cross Valley Formation is overlain by marine deposits of the La Maseta Formation (late Eocene-early Oligocene?).

Tertiary age deposits are also exposed on King George Island and include the Ezcurra Inlet Group (Paleocene), Fildes Peninsula Group (Eocene?), and Dufayel Island Group (Eocene). These deposits contain carbonaceous intervals [Birkenmajer, 1987] and a rich pollen and spore assemblage which reflects moist and warm climatic conditions [Stuchlik, 1981]. The climate of the peninsula region had begun to cool by Oligocene time, as indicated by more temperate pollen and spore assemblages within the Polinia Glacier Group and the Point Hennequin Group [Birkenmajer, 1987]. The oldest glacial deposits of the region are Oligocene and possibly Eocene in age [Birkenmajer, 1987]. These early glaciers existed in a temperate climate and are associated with interglacial deposits which are partly fluvial in origin. At this time, quartz-rich turbidites were being shed from the continent and onto the continental rise at DSDP Leg 35 site 325. By the middle Miocene the glacial setting

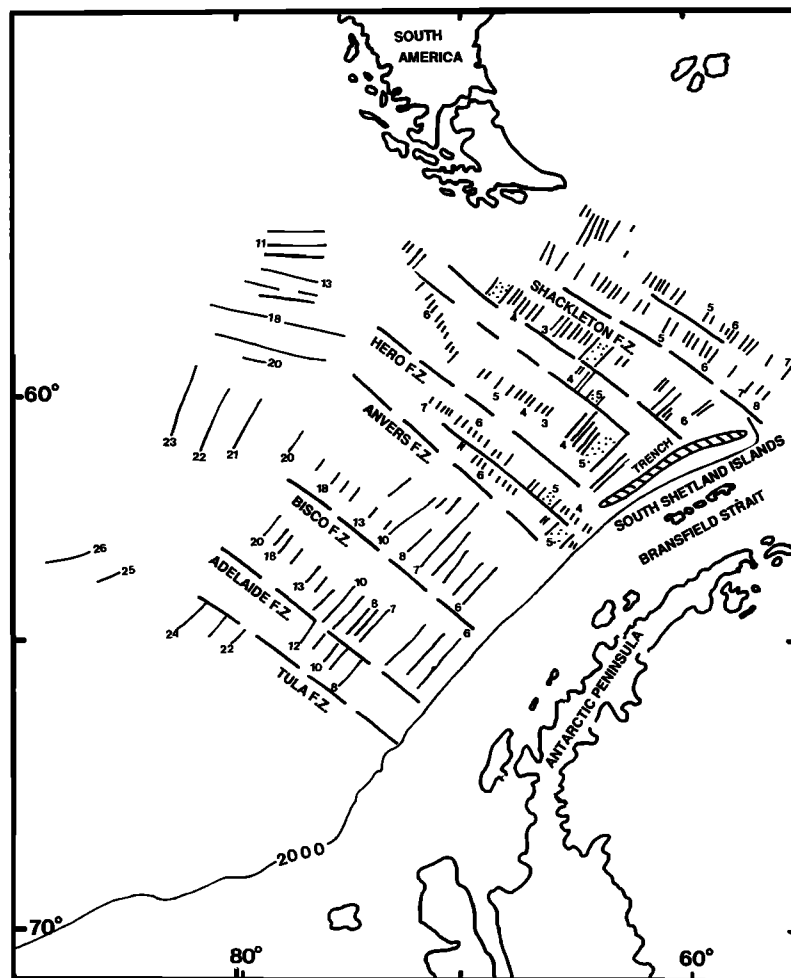


Fig. 14. Tectonic setting of the Antarctic Pacific sector [from *Barker, 1982*].

was perhaps similar to that of the present and glacial-marine sedimentation dominated on the continental margin.

Marine geophysical surveys of the Antarctic Peninsula sector were first conducted by Japanese scientists [Kimura, 1982], and later surveys were conducted by scientists from Brazil [Gamboa *et al.*, 1990], Great Britain [Larter and Barker, 1989], and the United States [Anderson *et al.*, 1990b, c]. The following discussion is based on the results of the U.S. survey, which was conducted between longitudes 63° and 68°W; 15 shelf transects and two strike lines on the shelf were acquired during this survey (Figure 15).

Seismic records from the continental shelf show four sequences (Figure 16). The oldest of these, sequence 4, is characterized by folded and faulted strata and thus consists of pre-tectonic and syntectonic deposits, presumably comprised of volcanoclastic material. Sequence 3 is an accretionary sequence which rests sharply on

sequence 4. This sequence marks the onset of passive margin conditions. The thickness of the sequence increases from northeast to southwest, which is consistent with an earlier age of ridge subduction in that direction and thus a more prolonged interval of passive margin development. The maximum age of this sequence within each tectonic segment of the margin, as derived from the magnetic anomaly nearest the continental margin, is given in Figure 15.

Sequence 3 was deeply eroded to form the U2 unconformity, which is present everywhere on the shelf and extends to the shelf edge (Figure 16). This unconformity marks the first of several glacial erosional episodes on the shelf. After that time the shelf was overdeepened by this erosion, and sedimentation there was regulated by glacial-marine processes.

There are two old forearc basins preserved on the continental shelf within the survey area (Figure 15); these are the only portions of the inner shelf where

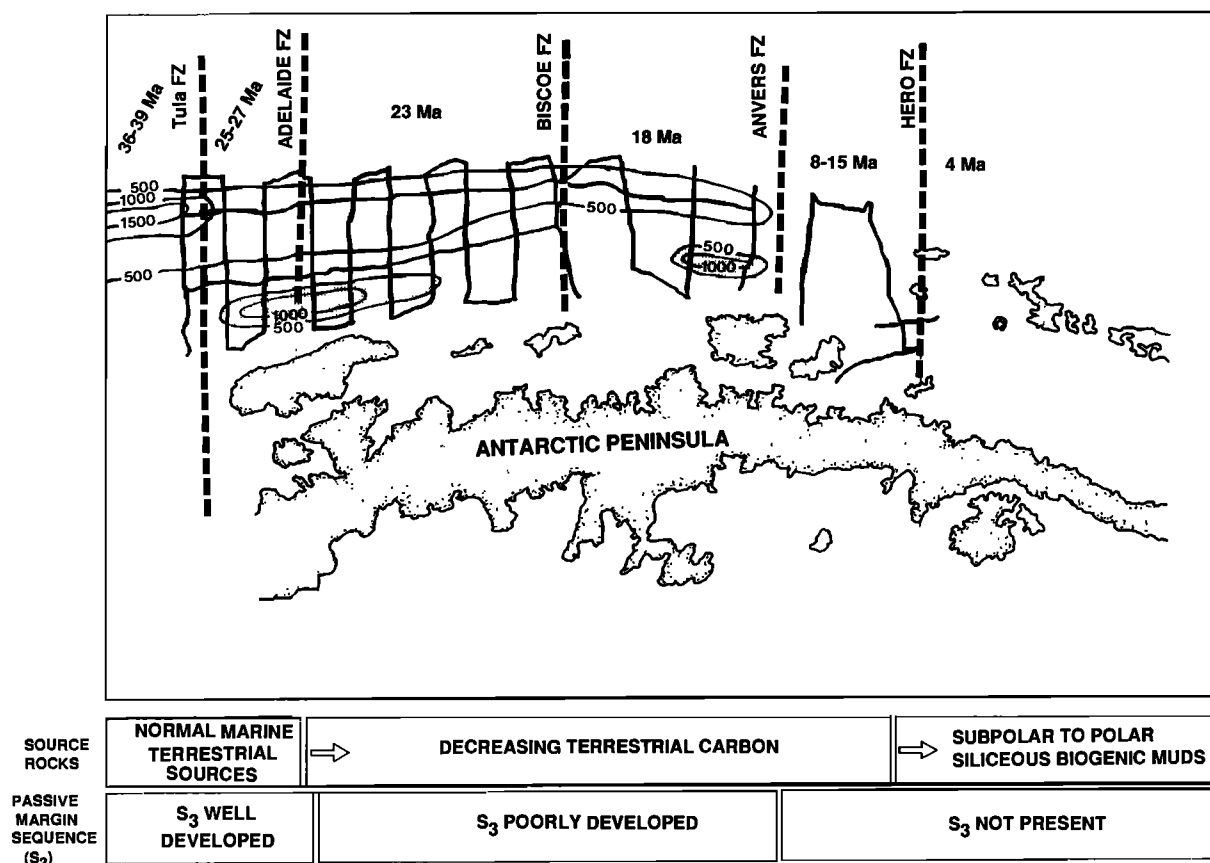


Fig. 15. Tectonic segments of the Antarctic Peninsula margin; heavy dashed lines are fracture zones. The age of ridge subduction within each segment is also provided. The shaded contours show the thickness of pre-tectonic and syntectonic deposits that fill old forearc basins on the inner shelf. The open contours show the thickness of sequence 3, which is an accretionary sequence deposited after ridge subduction. The distribution of potential source rocks and reservoir rocks (presumed to occur mainly within sequence 3) are also shown. Solid lines are USAF-88 seismic lines.

significant sediment accumulations exist. Both basins are relatively small and contain less than a kilometer of sedimentary deposits, presumably consisting of volcanoclastic material. Elsewhere, thick sedimentary deposits are restricted to the outer shelf and slope south of the Anvers Fracture Zone. Total sediment thickness increases from northeast to southwest, owing mainly to an increase in the thickness of sequence 3. South of the Tula Fracture Zone, sequence 3 is in excess of 1500 m thick (Figure 15).

Hydrocarbon Potential

There is an abundance of potential source rocks exposed throughout the Antarctic Peninsula region. Conditions were suited for source rock formation throughout most of the Mesozoic and early Tertiary. Having been subjected to the high heat flow from the subducting spreading center, these deposits have likely generated hydrocarbons.

The period of time between ridge subduction (passive margin development) and the onset of subpolar glacial conditions in the Pacific-Antarctic sector is crucial to the hydrocarbon potential within each segment of the shelf; this is the time window during which conditions were most suited for the formation of siliciclastic reservoir rocks. During the interval of active margin development, volcanoclastic sediments were deposited on the shelf. The development of subpolar glacial conditions in the Antarctic Peninsula resulted in a dramatic change in the style of sedimentation on the shelf, most importantly the deposition of poorly sorted glacial-marine deposits that are considered unsuitable reservoir rocks. The highest hydrocarbon potential lies south of the Tula Fracture Zone on the Bellingshausen and Amundsen shelves where sequence 3 is thickest and where potential source rocks of sequence 4 are buried the deepest. Tectonic segments north of the Tula Fracture Zone are considered marginal to poor in terms of their hydrocarbon potential.

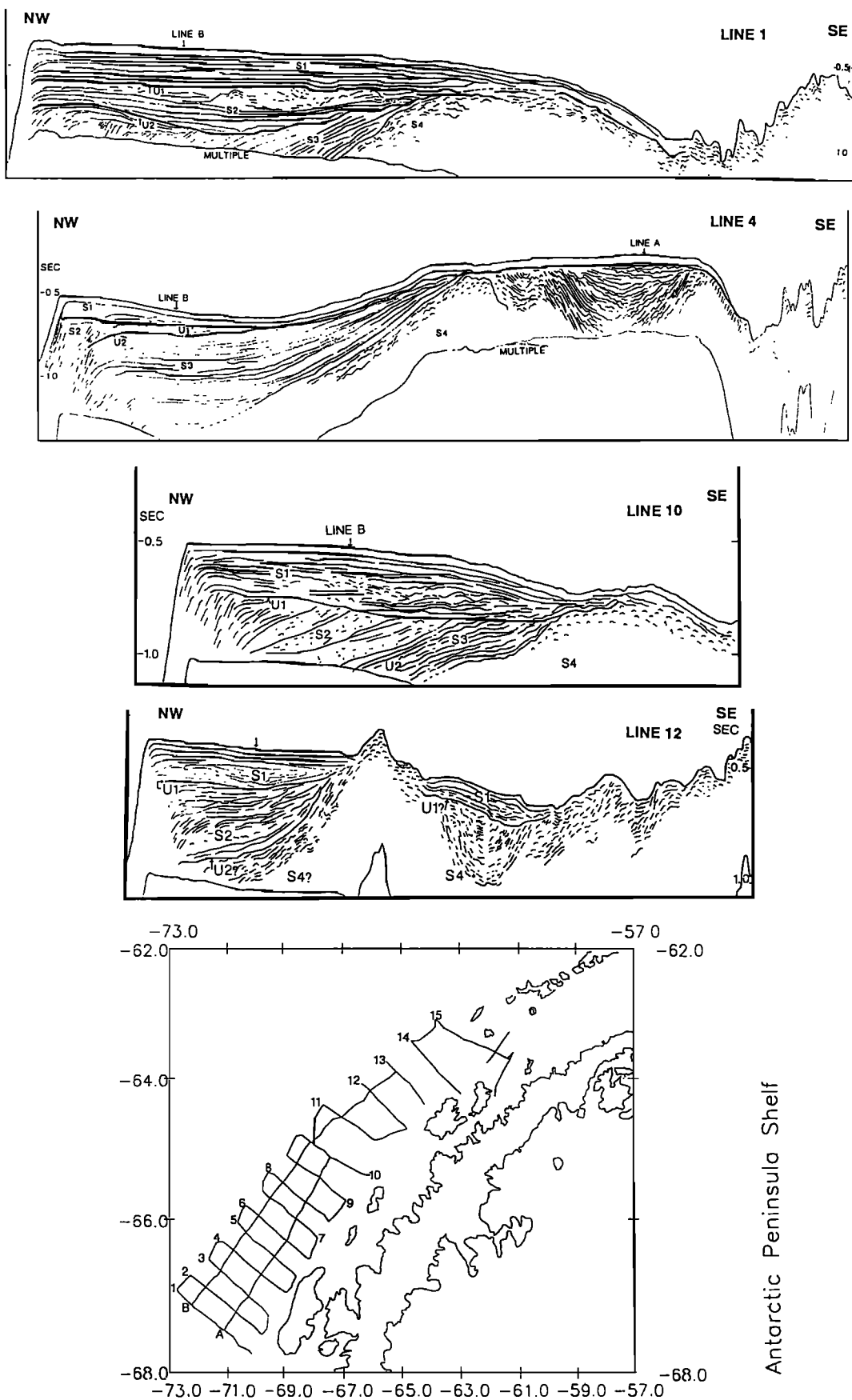


Fig. 16. Representative interpreted seismic reflection profiles from the Antarctic Peninsula shelf.

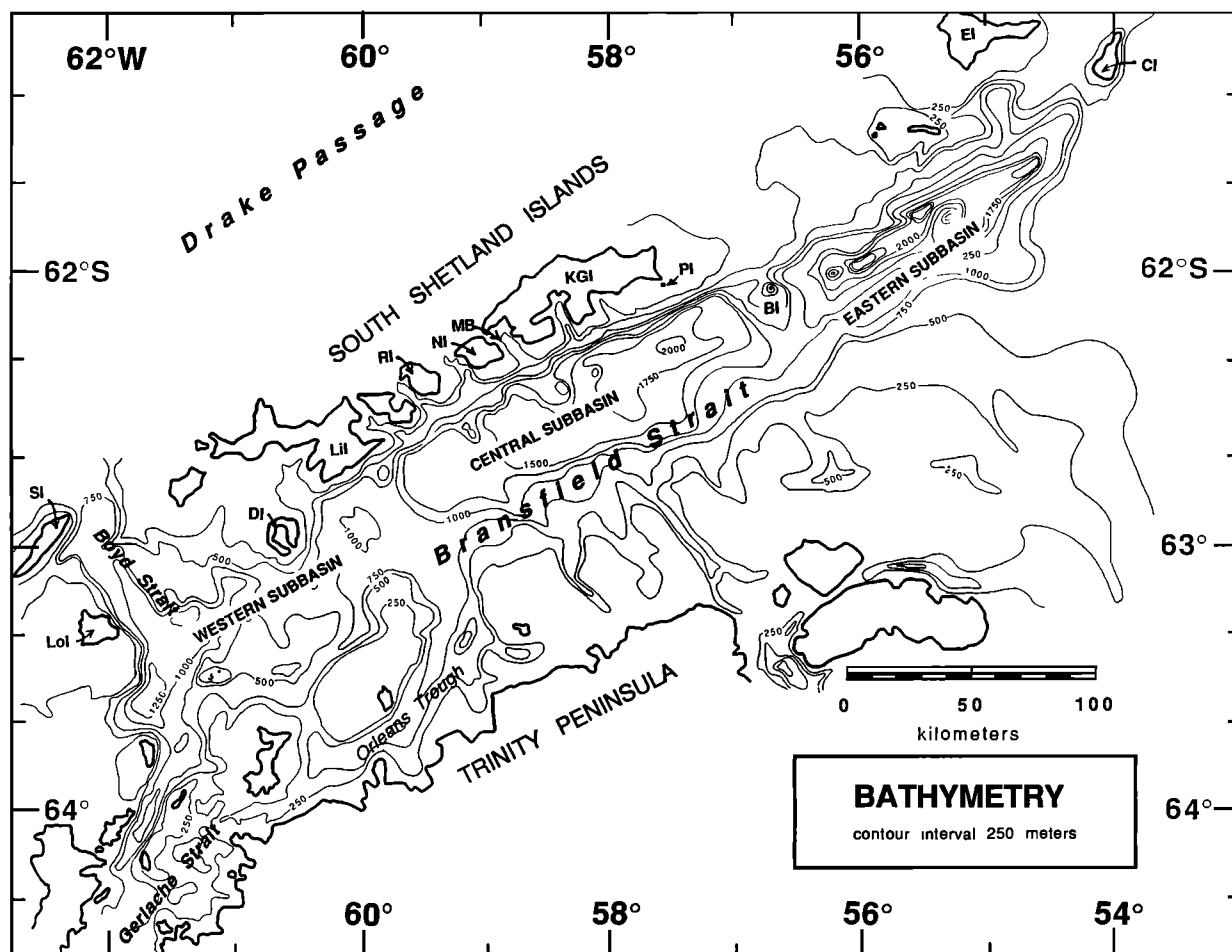


Fig. 17. Bathymetry of the Bransfield Strait showing three subbasins, the western subbasin, the central subbasin, and the eastern subbasin. Also shown are the locations of seismic profiles DF86-14, DF86-11, and PD86-12, which are shown in Figure 18.

BRANSFIELD BASIN

Geology

Bransfield Strait is an extensional basin separating the South Shetland Islands from the northern Antarctic Peninsula. It is approximately 100 km wide and is confined to that portion of the Pacific-Antarctic margin between the Hero Fracture Zone and the Shackleton Fracture Zone (Figure 14). Recent volcanic activity on Deception Island [Weaver *et al.*, 1979] and seismic activity along the axis of the Bransfield Strait [Forsyth, 1975; Pelayo and Wiens, 1986] imply that extension is continuing, while south of the Hero Fracture Zone the margin has become passive [Barker, 1982]. Barker and Dalziel [1983] have postulated that extension of the basin resulted as subduction beneath the South Shetland Trench ceased, about 4 m.y. ago, owing to continued

cooling and sinking of the subducted slab. Hence this is a relatively young sedimentary basin.

Segmentation of the Bransfield Basin is attributed to differences in subduction processes across minor fracture zones [Jeffers *et al.*, 1990]. Jeffers *et al.* [1990] argue that since these minor fracture zones have been at fixed positions along the margin, this second-order segmentation may have influenced the margin for several tens of millions of years before subduction stopped.

No sites have been drilled in the Bransfield Basin. Jeffers and Anderson [1990] have proposed a sequence stratigraphic model for the basin that is based on single-channel seismic data and piston cores. Their model calls for major differences in high-stand/interglacial versus low-stand/glacial maximum depositional systems, with thick sedimentary wedges accumulating on the Trinity Peninsula and South Shetland platforms during high

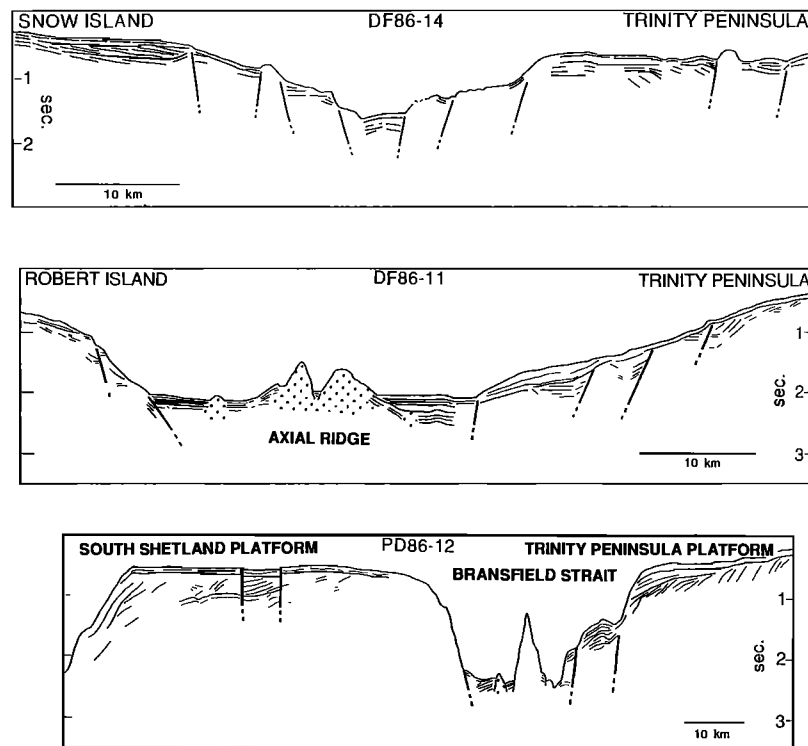


Fig. 18. Interpreted seismic reflection profiles from the Bransfield Basin. (See Figure 16 for profile locations.)

stands and significant fan accumulation in the central axis of the basin during low stands.

Geophysical surveys of the Bransfield Basin have been conducted by British, West German, Brazilian, Polish, and U.S. scientists, but detailed results of these surveys have not been published to date. The following discussion is based mainly on data acquired during several U.S. expeditions to the area.

The Bransfield Basin is divided into three subbasins which are clearly shown by the overall morphology of the basin (Figure 17). The western subbasin is relatively shallow and narrow, the central subbasin is over 2000 m deep and wider than the western subbasin, and the eastern subbasin is in places more than 2500 m deep and approximately as wide as the central subbasin (Figure 17). Geophysical data from the region indicate that the three subbasins represent discrete tectonic segments with different tectonic and depositional histories [Jeffers *et al.*, 1990]. The boundaries between these subbasins separate areas of different crustal structure [Ashcroft, 1972] and different amounts of seismic activity [Pelayo and Wiens, 1986]. Furthermore, the aeromagnetic map of the area [Renner *et al.*, 1985] shows offsets along these boundaries. Lastly, seismic reflection profiles from the region show important differences in the structural style of each basin, as illustrated in Figure 18. The western subbasin is a narrow, fault-bounded basin with

a thin (<1 km) sediment fill near its center (Figure 18). The central subbasin has an axial ridge that extends the entire length of its central trough (Figure 18). Sediments are thickest on the southern (peninsula) side of the ridge, where they exceed 1 km near the axial ridge and may be several kilometers thick on the Trinity Peninsula margin. The eastern subbasin has a discontinuous axial ridge, a relatively thick sediment fill near the axis of the basin, and thick sedimentary sequences on both the Trinity Peninsula Platform and on the South Shetland Platform (Figure 18).

Hydrocarbon Potential

Potential source rocks are probably widespread in the Bransfield basin. Carbonaceous sediments have been described in the Paleogene exposures on King George Island [Birkenmajer, 1987] and in Mesozoic and Paleogene exposures of the Antarctic Peninsula region (see Weddell Sea section). Furthermore, potential source material is abundant in the more recent sediments that fill the basin in the form of organic-rich diatomaceous muds. High heat flow is indicated by subsea volcanism. This situation allows for rapid maturation, and hydrothermal circulation provides a mechanism for flushing hydrocarbons out of source rocks at relatively low overburden pressures. Suess [1987] documented an

extensive zone of hydrothermal activity along the axial ridge of fluid advection through its thick sedimentary cover. In addition to vertical fluid migration, *Han and Suess* [1987] report widespread lateral pore fluid advection through relatively permeable turbidite layers. Lastly, direct oil shows in near-surface sediments have been reported by several workers in the area [*Whiticar et al.*, 1985].

The primary unknown concerning hydrocarbon prospectivity in the Bransfield Basin has to do with the occurrence of suitable reservoir rocks there. *Jeffers and Anderson's* [1990] seismic stratigraphic model predicts that terrigenous clastics might be deposited during low-stand/glacial maxima as shelf-margin and trough-outlet wedges and as basin floor fans. However, because petroleum is generated at very shallow depths, there may not be adequate structure to form traps. Very little faulting is observed in postrift deposits. If significant petroleum reserves are present, they probably occur in highly faulted prift deposits or are associated with stratigraphic traps.

CONCLUSIONS

Large oil and gas fields, and possibly even some giant fields, probably exist on the Antarctic continental margin. Thick sedimentary sequences with potential source rocks and reservoirs occur in every part of the margin surveyed to date, with the possible exception of the northern part of the Pacific-Antarctic margin and the Bransfield Basin. The logistical obstacles and hazards which must be overcome in exploiting these resources are immense.

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THE RESOURCE POTENTIAL OF ANTARCTIC ICEBERGS

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The possible use of Antarctic icebergs as a source of water and electrical power is discussed. We review the history of the idea, the development of concepts of iceberg use from the 1950s onward, and the physical properties of icebergs which determine their susceptibility to decay and thus their likely survival time under tow. The elements of an iceberg utilization scheme are discussed, including potential destinations, iceberg detection and selection, propulsion, protection, and processing. An "Icetek" scheme which combines water utilization with power generation via ocean thermal energy conversion would seem to offer the best economic prospect for iceberg use, but many technical problems remain unsolved while fundamental physical processes affecting an iceberg tow have yet to be examined experimentally.

INTRODUCTION

The greatest and most obvious resource of Antarctica is the water locked up in its ice cover. The volume of the Antarctic ice sheet is $2.8 \times 10^7 \text{ km}^3$ [Untersteiner, 1984], which represents 70% of the total "standing stock" of freshwater in the world, including groundwater sources [Skinner and Turekian, 1973]. These staggering figures immediately indicate the desirability of making use of this untapped water resource. However, short of mining the ice in situ we cannot utilize the standing stock of ice, but only the flux of ice emitted from the ice sheet in the form of icebergs.

The calving of icebergs is a major mechanism for ablation from the Antarctic ice sheet, with additional contributions from basal melting of ice shelves and from runoff and sublimation. Assuming that the Antarctic ice sheet is in a neutral or slightly positive state of mass balance [Dolgushin *et al.*, 1962; Hollin, 1970], this suggests that the iceberg flux should be a significant function of the rate of snowfall over the Antarctic continent. Iceberg flux has been estimated to be of the order of $10^3 \text{ km}^3 \text{ yr}^{-1}$ [Mellor, 1967] but with large fluctuations due to the occasional breakout of major ice tongues. A mass estimate, in reasonable agreement with this, was $(1.63 \pm 0.10) \times 10^{15} \text{ kg yr}^{-1}$, by Shumskiy *et al.* [1964]. A more recent estimate is by Orheim [1984], who makes use of the large observational data set collected by ships of opportunity and transmitted in standard format to Norsk Polarinstitutt. From 33,000 sightings of icebergs he used statistical arguments to derive an estimate of $2.3 \times 10^{15} \text{ kg}$ (i.e., about $2.7 \times 10^3 \text{ km}^3$) for the mean annual iceberg flux, which would give the Antarctic ice sheet a negative mass balance.

This, then, is the maximum freshwater volume avail-

able annually. By comparison, the mean flow rate of the Amazon River is $5.7 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$, roughly double the Antarctic iceberg flux [Dietrich *et al.*, 1980]. Therefore icebergs could make a significant addition to the world's water supplies, but only if most of those produced were captured. Since the annual flux represents about 5000–10,000 individual bergs, this is an impossible task; so the global contribution of icebergs to the world's usable water can only be a minor one. However, iceberg water is available in a ready-packaged form, and as we shall see, there are a number of destinations and types of iceberg water scheme which may be economically attractive and technically feasible.

HISTORY OF THE IDEA

The economic use of natural ice as a refrigerant has a very long history [Reynolds, 1979, 1983]. The Romans used ice from Alpine lakes, which was transported in straw to Rome. By the early nineteenth century the use of lake ice was widespread throughout Europe and North America. Ice was cut from lakes during winter and stored in insulated ice houses for summer use. Thoreau [1854] gives a classic description of ice cutting on Walden Pond. Where a nation such as Great Britain needed ice for refrigeration (the preservation of fish, in particular, required large quantities) but was unable to supply it herself, an export trade developed from more northerly countries. Norway began exporting glacier ice to Britain in 1822, and by 1898, 550,000 tons were being exported annually to Britain, France, and Germany. The ice was taken from ice caps such as Folgefonni (southwestern Norway) and Jøkulfjordbreen near Tromsø and was mined either by the use of explosives

on the snout of the glacier or by netting fragments of ice which calved into a lake.

In the United States a source of ice for the expanding cities of California was Alaska, and a trade developed in lake ice and in ice from the Baird Glacier [Keithahn, 1967]. In all cases the ice was transported by ship, but in the 1890s it appears that the first case of iceberg towing occurred, when small icebergs were towed from Laguna San Rafael in southern Chile to Valparaiso and Callao [Weeks and Campbell, 1973]. Little documentation of this event is available.

With the development of artificial refrigeration the natural ice trade died out. It was in the 1950s that the new idea of using icebergs as a source of freshwater for drinking or irrigation arose through an unpublished study by John D. Isaacs of Scripps Institution of Oceanography (reported in the work of Burt [1956a, b] and Engel [1961]). The intention was to relieve California's water shortage by towing small Alaskan icebergs southward or large Antarctic icebergs northward. The proposal led to much discussion at Scripps, with the general conclusion that such a project would be feasible. During the 1960s and early 1970s a successful technology of iceberg towing was developed for the Labrador Sea and Grand Banks region, where icebergs have to be towed out of the way of drilling rigs. The technique involves passing a buoyed line around the berg, from which bridles are connected to one or more tugs. Much experience has now been gained in the measurement of bollard pulls needed to move bergs of different sizes and in the development of methods of decoupling the towing vessel from hazardous iceberg behavior such as rolling.

Isaacs' proposal was revived in 1973 in two major studies, by Weeks and Campbell (dealing with tows to southern hemisphere destinations) and by Hult and Ostrander (dealing with tows to California). The Hult and Ostrander paper considered the towing of trains of insulated icebergs, which went well beyond the limits of current technology. The Weeks and Campbell paper dealt with the more modest aim of an unprotected tow through a minimum distance to a southern hemisphere coastal desert location. They analyzed power requirements, routes, melt rates, and costs and concluded that a large tabular berg could be delivered to a site such as the Atacama Desert or Western Australia for a few thousandths of a cent per cubic meter, a small fraction of the cost of desalination. The unknown additional cost of processing the berg may still allow the overall economics to be attractive, even if the water is intended for low-value uses such as irrigation.

Rapid development of the concept ensued, largely through the interest of Prince Mohammed Al-Faisal Al-Saud of Saudi Arabia, who envisaged the use of iceberg water as a solution to Saudi Arabia's drinking water shortage. This high-value use would, he hoped, offset the vastly greater cost of a northern hemisphere

tow where the berg would need total protection from the sea for its passage through the Tropics. Prince Faisal supported many feasibility studies, leading to a First Conference on the Use of Icebergs, held at Ames, Iowa, in 1977 [Husseiny, 1978]. The 61 papers presented at this conference included many ingenious technical ideas for handling icebergs but revealed the depth of our basic scientific ignorance about iceberg properties. Increased activity in basic research followed, and the more restrained Second Conference on the Use of Icebergs, held at Scott Polar Research Institute, Cambridge, in 1980 [Annals of Glaciology, 1980] featured more data and less speculation. The consensus of the participants was that the original concept of Weeks and Campbell still seemed valid, that problems of iceberg stability and of processing icebergs at the destination were crucial and still unsolved, that no workable means of iceberg insulation had yet been devised so that northern hemisphere tows were as yet unfeasible, and that the economics could be improved by combining the iceberg processing with an ocean thermal energy conversion scheme to simultaneously generate electricity. This consensus on problems and prospects still holds at the time of this writing, and there is general agreement that an experimental tow to, say, Australia, is the next logical step and the best way of testing theories about resistance, melt problems, and towing costs.

PHYSICAL PROPERTIES OF ICEBERGS

Tabular icebergs originate from the calving of the ice shelves which occupy about one third of the coastline of Antarctica (Figure 1). The shelves are fed at their landward ends by ice from the Antarctic ice sheet, and their seaward ends are afloat, meeting the ocean in cliffs of typical freeboard 30–40 m and total thickness 200–300 m. The ice shelves advance at typical speeds of 0.3–2.6 km yr⁻¹, and the seaward edges calve off through a variety of stresses (current, tidal, the pressure of drifting pack) which act on the most exposed portions. Specific mechanisms have not been studied, except in the special case of glacier tongues, such as the Erebus Glacier Tongue in McMurdo Sound [Holdsworth and Glynn, 1978], where long ocean waves are thought to cause the tongue to oscillate until it fails in flexure. Some apparently minor ice shelves are prolific generators of icebergs because of their rapid velocity; the Amery Ice Shelf, for instance, although small in size, drains 1/8 of the Antarctic ice sheet and produces 31 km³ of iceberg volume per year [Budd et al., 1967].

After calving, the new iceberg drifts in the approximate direction of the Ekman transport, which is initially westward along the coast with the East Wind Drift. The iceberg may run aground at this stage and remain aground for several years; Figure 2 shows the drift track of the very large iceberg "Trolltunga" which broke off

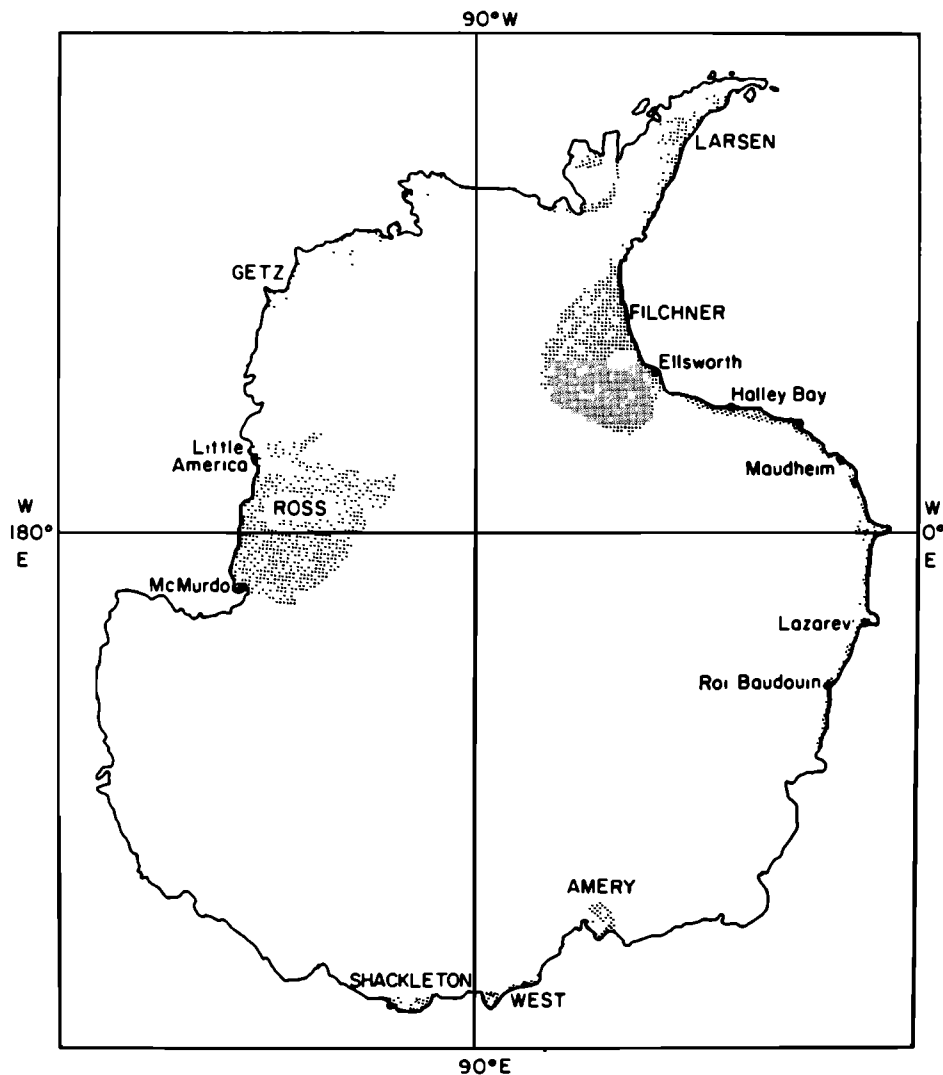


Fig. 1. The main ice shelves surrounding the Antarctic continent [after Weeks and Mellor, 1978].

the Fimbul Ice Shelf at about 0° in 1967 and then ran aground in the southern Weddell Sea for 5 years [Vinje, 1979]. Eventually, the berg breaks away from the coast and comes under the influence of the West Wind Drift (Antarctic Circumpolar Current), in which its long-term average drift is ENE. Tchernia and Jeannin [1984] found that this curvature away from the coast tends to occur at four well-defined longitudes or “retroflexion zones” (Figure 3), situated in the Weddell Sea, east of the Kerguelen Plateau at 90°E , west of the Balleny Islands at 150°E , and in the northeastern Ross Sea. These are related to the partial division of the water south of the Antarctic Circumpolar Current into gyres such as the Weddell and Ross sea gyres and suggest that icebergs found at low latitudes may originate from some particular sector of the Antarctic coast.

Clearly, a freshly calved iceberg possesses the same structure and physical properties as its parent ice shelf. The most important property for the iceberg’s survival is its density distribution. Figure 4 shows some typical density profiles through ice shelves. The uppermost 40–60 m has the lowest density, as it originates from the most recent snow deposition, and does not reach the density of 800 kg m^{-3} necessary to close off the pores and channels between the crystal grains. This means that the above-water portion of a typical berg is entirely composed of material which should be described as “firn” rather than “ice,” permeable both to water and air. This crucial fact affects the subsequent history of the iceberg.

Figure 5 shows some typical temperature profiles through ice shelves together with a profile through the

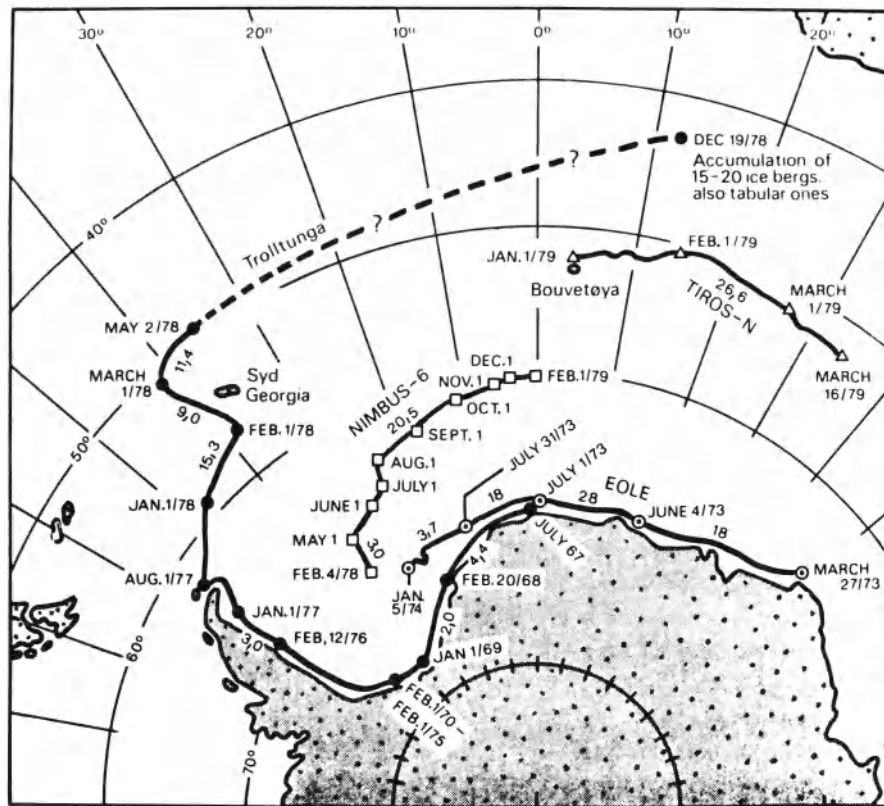


Fig. 2. Drift trajectories of some satellite-tracked icebergs in the Atlantic sector [after Vinje, 1979]. The large berg "Trolltunga" was last observed on May 2, 1978; a group of bergs later seen at 12°E is believed to be the fragmented remains of Trolltunga.

upper layers of a recently calved berg [Orheim, 1980]. Already the upper part of the berg is significantly warmer than its parent ice shelf. As soon as the berg drifts into more temperate regions, especially when it drifts free of a surrounding pack ice cover, it begins to melt at its upper surface. The meltwater percolates through the permeable uppermost 40–60 m, refreezing at depth and giving up its latent heat. By this means the above-water portion of an iceberg is brought relatively quickly to temperatures close to the melting point. With its warm temperature and its low density, this part of the berg becomes extremely weak and can be easily eroded away. The remaining strength of the berg lies in the "cold core" below sea level.

When the berg frees itself from the sea ice cover, it also becomes subject to wave action. The high level of turbulence around the waterline increases the heat transport into the ice and preferentially melts out a "wave cut" which can penetrate for several meters into the berg. At the same time the turbulence level is enhanced around existing irregularities in the berg, such as cracks and crevasses. Waves eat their way into these like sugar eating its way into a tooth cavity, turning

cracks into caves whose unsupported roofs may then collapse. An iceberg often leaves a trail of detritus from such processes behind it in the form of growlers, brash, and bergy bits. In advanced cases of waterline erosion the above-water portion of the berg is broken up into a number of independent elements (Figure 6), creating a "drydock" or "pinnacled" berg.

Apart from decay of this kind which is accelerated by mechanical erosion, melt also occurs from the sidewalls and bottom of the berg. There is considerable literature on sidewall melt rates as a function of the temperature and salinity profile of the water column. Depending on details of the temperature-salinity profile, upwelling or downwelling of water near the ice-water interface may occur, and the melt may produce stable layering in the nearby water. All of these studies have been based on theoretical reasoning or on laboratory scale tests, and all refer to melt in still water. There has been very little work on what realistic melt rates will be, given that even under natural drift there will always be an ice-water relative velocity at some depths (because of the Ekman spiral), while during towing this will be much enhanced. Some model scale tests on towed ice blocks have been

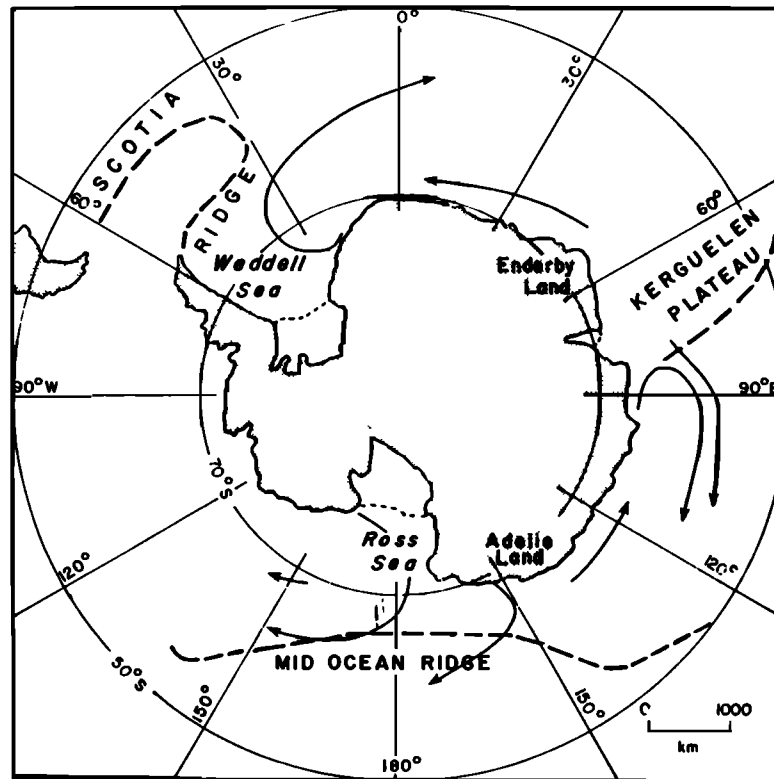


Fig. 3. Main trends of movement shown by satellite-tracked icebergs in the Antarctic Ocean [after Tchernia and Jeannin, 1984].

done and suggest that an iceberg under tow will become more shipshape and streamlined, with preferential erosion of upstream corners, but valid quantitative conclusions can only come from full-scale tests. These questions are discussed further in the section on propulsion.

Another important property of large tabular bergs is the fact that they flex under the influence of long ocean waves. The flexural response of Arctic ice islands to wave action has been studied theoretically and experimentally by Goodman *et al.* [1980], and in 1981 and 1982 this study was extended to direct experiments on Antarctic tabular iceberg flexure [Wadhams *et al.*, 1983]. The measurements revealed significant bending even in moderate seas. When the sea state is extrapolated to that which would occur in a typical Southern Ocean storm, the conclusion was that most large tabular bergs would be in danger of breaking up under the wave-induced flexure. Support for this conclusion comes from studies of berg size distribution in the open sea and in the sheltered pack ice zone [Hult and Ostrander, 1974]. The greatly increased number of small bergs seen in the open sea is more than would be expected by pure melt of large bergs but must result from their fragmentation. This may be a serious, or even fatal, drawback to iceberg utilization.

An eroded berg may suffer reduced stability to roll and be in danger of capsizing. This is less common in the Antarctic than in the Arctic but in the later stages of a tow may be significant. A berg's stability can be monitored by the use of tiltmeters; a long period of roll implies reduced stability [Kristensen *et al.*, 1982].

ELEMENTS OF AN ICEBERG UTILIZATION SCHEME

In light of the known physical properties and behavior of icebergs and assuming that methods of protection are not technically or economically feasible, a possible iceberg utilization scheme must confine itself to southern hemisphere destinations. An ideal destination should have the following properties: (1) cold surface water and favorable currents along all or most of the route of the tow, to minimize total towing effort and en route melting; (2) deep water close inshore, to minimize the problems of transporting fragments of processed iceberg to shore-based facilities; and (3) a serious local need for water, either for irrigation or for drinking, to minimize costs of long-distance pipelines or other distribution systems.

There are three regions which satisfy these criteria:

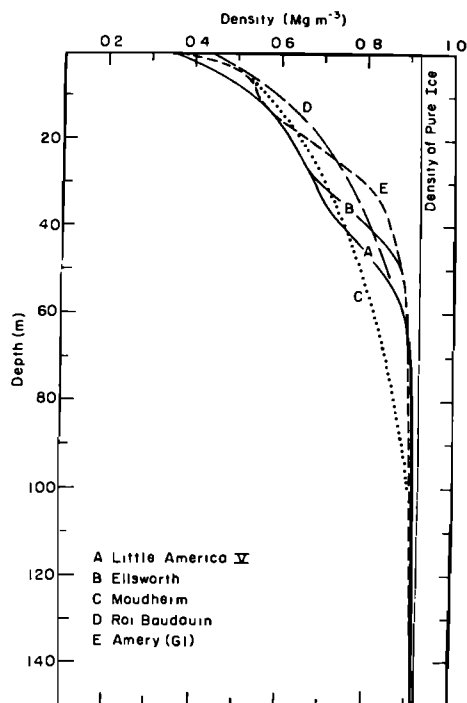


Fig. 4. Density profiles through some typical ice shelves [after Weeks and Mellor, 1978].

1. The first region is the Atacama Desert coast of northern Chile and southern Peru, where the cold northward flowing Humboldt Current provides a favorable temperature and drift environment for a berg being brought up from Antarctica, where the continental shelf is very narrow (less than 20 km in places), and where a greatly enhanced level of agricultural production would be possible with better irrigation. It is noteworthy that the Mochica culture from the third millennium B.C. onward achieved a high level of civilization and productivity in this area through the use of complex irrigation systems [Von Hagen, 1964].

2. The second region is the Namib Desert region of southern Angola, Namibia, and South Africa. Here there is a zone of cold upwelling near shore, a narrow continental shelf, and a coastal desert in which agricultural settlements could be established if a water source were available.

3. The third region is Western Australia and the Great Australian Bight. Cold water is not far away to the south, there are locations where deep water reaches close inshore (e.g., Rottnest Island off Perth), and the need for desert irrigation is complemented by a drinking water requirement for cities such as Perth and Fremantle which at present use a dwindling groundwater reservoir.

Figure 7 shows contours of surface water temperature and their relation to these potential destination regions.

When a destination is determined for the first iceberg scheme, the elements of technology which must be developed and put in place comprise (1) iceberg detection and selection technology; (2) propulsion to the coastal destination; (3) protection en route, if feasible; and (4) processing at the coast, comprising all the steps from the point at which the whole iceberg is run aground or moored at about the 200-m depth contour to the point at which meltwater and/or electricity flow out from the nearby coastal processing plant. We consider these steps in turn.

ICEBERG DETECTION AND SELECTION

Selection of the target berg for towing involves the following stages: (1) definition of a "target zone" within which a search is made, (2) location of all potential bergs within the target zone, and (3) survey for possible bergs to select only those with desirable characteristics.

The "target zone" is chosen from a knowledge of the basic current and wind patterns in the Southern Ocean. Since the long-term Ekman transport in the West Wind Drift appears to be ENE, a suitable target zone for bergs whose destination is southern Africa would encompass much of the southern South Atlantic, the zone for Australian destinations would be the southern Indian Ocean, and the zone for Chilean or Peruvian destinations would be the southeast Pacific.

The specific dimensions of the target zone depend on a trade-off between the desire for a short towing distance and the desirability of capturing an iceberg which is relatively young and not decayed. Icebergs near the

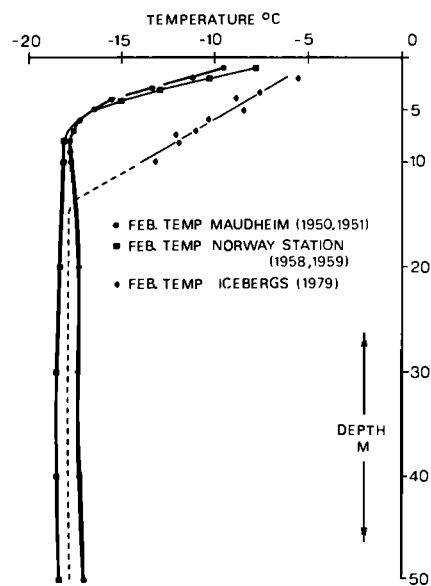


Fig. 5. Temperature profiles through the uppermost 10 m of some icebergs near the Antarctic coast, compared with the temperatures of some nearby ice shelves [after Orheim, 1980].



Fig. 6. A pair of pinnacled or drydock icebergs observed near the South Sandwich Islands. In each case a number of independent surface-piercing blocks are connected to a single submerged main body, the result of erosion of the upper part of the berg (photograph by the author).

northern limit of natural occurrence would offer the shortest towing paths but are mostly in an advanced state of melt [Wadhams, 1988]. An iceberg chosen from further south must be towed through a greater distance but is more likely to be strong enough to survive the tow. For each destination, it should be relatively easy to use long-term average current and wind patterns to generate contours of "equal towing time" for some specified towing speed, utilizing one of the many models of iceberg drift response developed for North Atlantic use [e.g., Sodhi and El-Tahan, 1980; Gaskill and Rochester, 1984]. With knowledge of water temperatures along these routes and an improved knowledge of melt rates as a function of tow speed and water temperature, such a chart of "towing isochrones" could be converted into a chart with contours of equal melt loss. The maximum acceptable melt loss in meters would then define the outer perimeter of the "target zone."

Having defined a target zone, the identification of potential bergs within the zone is, or will be, relatively simple. From 1991 onward there will be a number of satellites in near-polar orbits possessing synthetic aperture radar (SAR) systems, which can sense ice targets in water with a resolution of better than 50 m, during day or night and through cloud [Thomas, 1984]. The first will

be the European Space Agency's ERS-1, in an 82° orbit. Provided suitable ground receiving facilities are constructed in the southern hemisphere, there will therefore be no problem about locating and tracking every iceberg within the target zone. The present haphazard satellite tracking facilities available through the visual or infrared channels of Landsat, SPOT, and NOAA AVHRR will thus be superseded.

Bergs which appear to fall within the desired size range (determined by the power of the tugs available, the facilities available at the processing plant, and the hydrodynamics of towage) would then be surveyed by air. Visual inspection of the sidewalls and top would show the presence of surface crevasses, cracks, deep wave cuts, or eroded caves (see Figure 8 for some examples) which would make the iceberg an undesirable object for a tow. Radio echo sounding, as used in 1981 [Wadhams *et al.*, 1983], from aircraft or helicopter would detect the presence of bottom crevasses or other major imperfections and would also give the thickness of the iceberg, which is required for use in the on-line computer program that a towing vessel would have to employ to tell it the optimum tow direction at any time.

If these tests suggest that an iceberg is a desirable candidate for towing, the final selection would be made

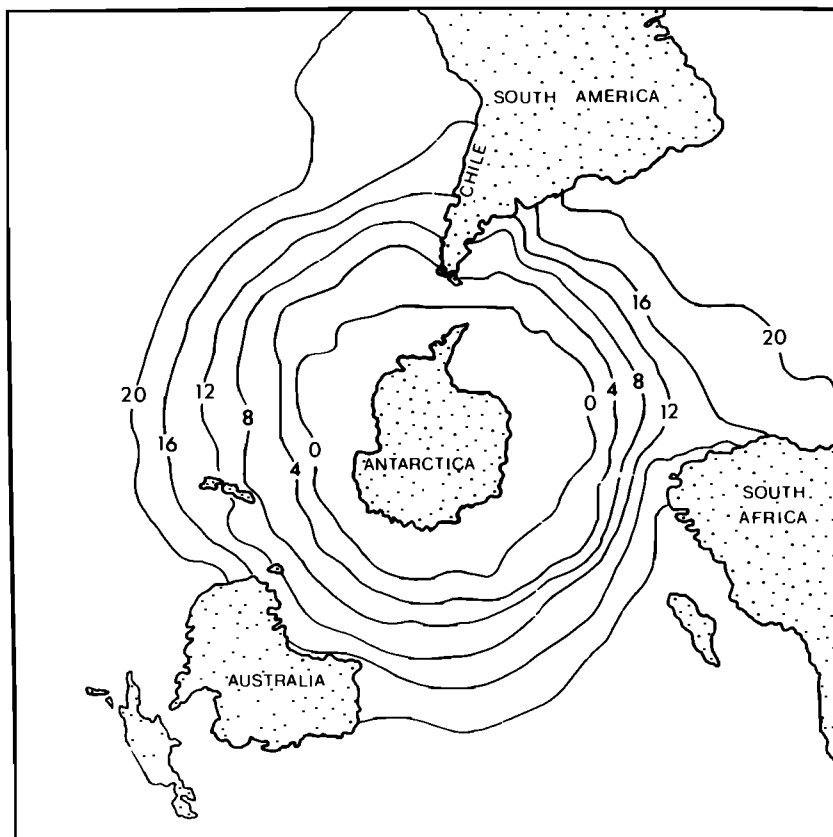


Fig. 7. Contours of Southern Ocean surface temperature at 4°C intervals, as observed by a U.S. Navy satellite in September 1977 (redrawn after Denner [1978]).

after a landing on the berg by helicopter to determine its near-surface temperature, its roll period, and similar vital indicators of its health.

PROPULSION

Having selected a berg, the next problem is to propel it to its destination. The obvious propulsion system is a conventional tug, but in the early days of enthusiasm for iceberg towing a number of exotic solutions were proposed [Husseiny, 1978], including paddle wheels, parachute drogues, and osmotic propulsion. A novel proposal was for a self-propelled iceberg driven by the temperature difference between surface seawater and iceberg meltwater which would fuel an ammonia-based turbine [Fuhs *et al.*, 1978]; this is similar to the "Icetek" concept discussed at the end of this paper. Another exotic proposal was for the use of arrays of kites [Nance, 1982]. All of these ideas founder on a basic property of icebergs, which is their tendency to lose mass by melting and calving, destroying any attempt at a built-in propulsion system. Current opinion therefore favors the use of conventional tugs. The probable method would be to attach a number of large tugs to a

floating bridle which surrounds the iceberg; this is the method already employed in the Labrador Sea for towing icebergs away from drilling rigs [Bruneau *et al.*, 1978; Benedict, 1978], and the use of multiple tugs overcomes the problem pointed out by Weeks and Mellor [1978] that the bollard pull needed to achieve a reasonable towing speed (about a knot) is beyond the capacity of any existing single wire rope. The use of a bridle makes the attachment and detachment of multiple tugs an easier matter, reduces the danger to the tugs if the iceberg capsizes, and may help to keep the berg together if it breaks into two or three large pieces through wave-induced flexure.

The hydrodynamics and cost factors involved in a tug tow were examined by Weeks and Mellor [1978] and by Job [1978a, b]. Two of the hydrodynamic problems are as follows:

1. What is the form drag coefficient of an iceberg, and how does it change during a tow? Does preferential melt cause the berg to become more streamlined?
2. What is the melt rate as a function of water temperature and towing speed?

Question 1 is susceptible to reasonable guesswork, a



Fig. 8. A tabular iceberg in which caves are being eroded at sites where parallel crevasses meet the sidewalls of the berg (after *Wadhams et al.* [1983]; photograph by M. Kristensen).

final drag coefficient of about 0.4 being a typical figure used in models. Question 2 revolves mainly around the effect that towing has upon the boundary layer close to the ice wall and is a basic question upon which the whole feasibility of iceberg towing may hang.

The melting of icebergs in still water with various types of stratification has been considered in a number of theoretical and experimental studies. Three modes of melting may be important: melting from the top, melting at the waterline due to wave erosion, and melting of the submerged sides and bottom. Little or no work has been done on melt rates from the top of a berg; in fact, it has been found that south of 66°S the melt rate is exceeded by the snow precipitation rate [*Orheim*, 1980]. It appears that the main effect of surface melt is to warm the above-water portion of the berg to the melting point by percolation and refreezing and thus weaken its resistance to the second mechanism, waterline wave erosion. This second process was studied on a laboratory scale by *Martin et al.* [1978], who found that waves excavated a cut which extended above the waterline to about 3/2 of the wave amplitude and below the waterline to about half a wavelength. The main erosive effect of this is to cause unsupported ice cliffs to collapse, so that

the berg leaves a trail of bergy bits behind it. The relative importance of this effect is unknown. Sidewall and bottom melting have been the subject of a large number of studies, not all of which agree. Bottom melt was the subject of a theoretical study by *Gade* [1979] and of laboratory experiments by *Martin and Kauffman* [1977] and *Russell-Head* [1980]. Very large differences occurred when the laboratory results were scaled up: e.g., *Russell-Head* predicted a 100 m yr^{-1} melt rate in water at 0°C, while *Gade* predicted 0.5 m. Much depends on whether processes were properly scaled in the experimental design. Sidewall melting has been the subject of theoretical and laboratory studies by *Neshyba* [1977], *Greisman* [1979], *Huppert* [1980], *Huppert and Josberger* [1980], *Josberger* [1982], and others. Their conclusion is that in uniform water an upwelling will occur at the ice-water boundary, while in stratified water the meltwater spreads out sideways to form layers of cells which give a steplike structure to the temperature-salinity profile near the berg. There is little information on the effect of a uniform flow past the iceberg on bottom or sidewall melt rates, the only experiments so far [*Stolfi et al.*, 1978] being the towing of small ice

masses in a bay, causing a distinct streamlining of the initial rectangular shape.

Weeks and Mellor [1978] summarized the diverse sources of evidence on melt in a very tentative rule of thumb, that

$$Z = KD$$

where Z is loss in meters from the outside of the iceberg per day (the bottom and sides being assumed to have the same melt rate), K is a constant of order 0.12, and D is mean water temperature in degrees Celsius averaged over the draft of the iceberg.

This rule yields, for instance, a loss of 120 m during a 100-day tow at an average water temperature of 10°C. For a berg of initial dimensions 1 or 2 km square by 200–300 m deep the bottom melt, if it is really as rapid as the sidewall melt, would clearly be the limiting factor in a tow, a loss of 100 m being probably the maximum acceptable. If the bottom melt rate is significantly lower than the sidewall melt rate, there would be a real advantage in towing a wide iceberg, since a considerable fraction will still remain at the destination. It is extremely important to test these relationships on a full scale by a properly controlled experimental tow of a full-sized tabular iceberg.

Given that the en route melt rate is the greatest unknown, the computation of the speed and course of a berg under a given towing force is reasonably robust. The analyses agree that the energies expended are relatively modest, although still very large in comparison with those involved in towing ships. *Weeks and Mellor*, for instance, estimated that a 400-m side by 200-m-thick berg of length 1600 m can be towed at 1 knot with a towing force of 6.9 MN, equivalent to a towrope power of 4760 hp. The bollard pulls involved exceed the capacity of the best available rope, but this can be solved with multiple tugs. Perhaps the main problem is that we are dealing with a very large, slow-moving body, whose natural motion under current, wind stress, and Coriolis force is only modified somewhat by the towing. The tug therefore cannot exert its pull in the direction in which motion is desired, since the towing force is only one of the polygon of forces of similar magnitudes. To apply the effort in the optimum direction, it will be necessary for the tug to have an on-line computer model running, in which a solution is continually updated for an optimum tow direction to minimize either transit time or en route melt or some combination of these factors (weighted by cost parameters). Such a model will require continual updating with environmental data on the berg itself (shape and instantaneous orientation), on the water structure locally, and on the surface pressure field and sea surface temperature field along the desired track. Satellites will be able to measure the last two parameters.

PROTECTION

The possibility of protecting icebergs from melt during transit was considered seriously at a time when tows to Saudi Arabia were envisaged. Various schemes were proposed, ranging from fabric wraps [*Hult*, 1978] to interlocking plastic sheets or foam [*Husseiny*, 1978]. Again, all such ideas foundered on the problem for dealing with natural erosion, which will simply carry away the insulation. Protection during a tow to the northern hemisphere is clearly essential, since all calculations agree that an unprotected iceberg will melt away completely. Even a tow to a southern hemisphere site such as Australia will involve a loss of some 50% of an iceberg's mass [*Job*, 1978a, b]; so even here protection would be beneficial.

The most important zone of protection is the waterline, to reduce or prevent wave erosion. One could envisage a vertical plastic curtain like an oil spill containment boom, but much deeper, which would damp out waves and at the same time contain some of the sidewall meltwater so that the iceberg would float surrounded by colder than normal surface water. The costs and design feasibility of such a boom, however, are unknown. At present, we must conclude that no satisfactory method of iceberg protection has been devised, that tows to the northern hemisphere are therefore impossible at present, and that southern hemisphere towing schemes must reckon on en route erosion being one of the major limiting factors to their effectiveness.

PROCESSING

Towing an iceberg successfully to a coastal site solves only part of the engineering problem of iceberg utilization. We assume that a site has been chosen where deep water reaches close inshore; even so, with a draft of 200 m or so, the iceberg will ground several kilometers offshore. First, the iceberg must be made fast. *Weeks and Mellor* [1978] showed that conventional anchoring systems, such as deadman anchors, will hold successfully even in the fairly weak firm that composes the top part of the berg. Multipoint conventional anchoring is therefore feasible.

The next problem is to reduce the berg to small enough pieces to be towed to the shore itself for melting and processing. The task must be accomplished as rapidly as possible because the berg will be melting quite fast while it lingers at its offshore site. *Weeks and Mellor* examined various engineering techniques, such as slicing the berg with electrothermal knives, making vertical cuts by presplit blasting, simple crater blasting, mechanical sawing, and crushing of the ice followed by pumping the fragments along a slurry pipeline to shore. Other ideas include starting off an artificial crack in the upper surface which is then deepened by filling it with water, the so-called "hydro-wedge" [*Smith*, 1978], and

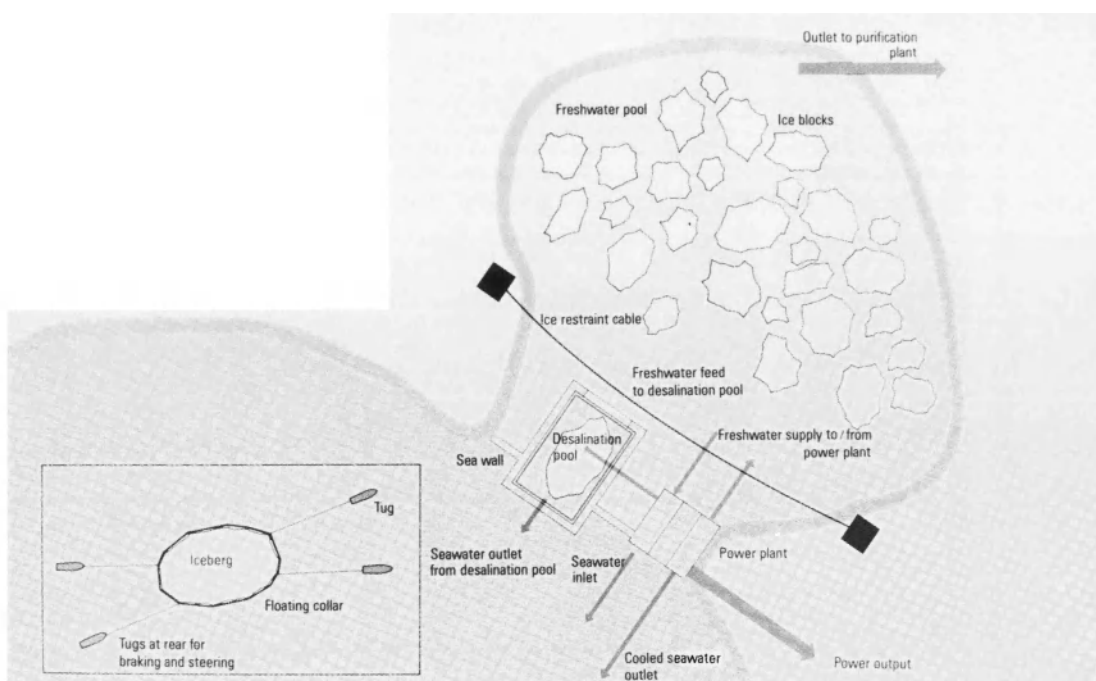


Fig. 9. Schematic diagram of a possible towing geometry and of an Ictec facility to process fragments from a berg moored offshore (after Wadhams [1982], redrawn from Heizer [1978]).

then separating fragments by horizontal blasting. Experimental studies in Newfoundland [Dieman, 1984] suggest that very cold ice, e.g., in the lower parts of an Antarctic berg, can be fragmented more easily than previously assumed by the use of slow-burning explosives such as thermit. Implantation of explosives after deep drilling may therefore be more efficient than near-surface blasting.

The consensus at present is that all these techniques are energy inefficient and that the cost of fragmenting a berg may be comparable to the cost of towing it from its capture point to the coast in the first place.

Once ashore, the energy costs of processing at first sight appear very large, because of the high latent heat of fusion of ice (33 kJ/kg). The alternatives are to allow the berg fragments to melt naturally, which would require a large lagoon to achieve a high enough melt rate to ensure rapid disposal of the berg fragments, or to apply energy to melt the fragments, which is wasteful and expensive. Fortunately the economics at this point have been transformed by the "Ictec" concept, by which the melting iceberg can be used to generate power through thermal energy conversion.

THE ICETEC CONCEPT

The high latent heat of fusion of water implies that a very large amount of energy is locked in an iceberg in

this form. It was suggested in 1977 that this energy could be used to provide electric power and thus increase the economic return that can be obtained from an iceberg [Heizer, 1978; Roberts, 1978; DeMarle, 1979]. DeMarle [1980] worked out and costed a specific scheme for Saldanha Bay in South Africa, where there is a lagoon suitable for storage of iceberg fragments and where the cold Benguela Current and a local upwelling combine to ensure a modest natural melt rate for moored icebergs.

The concept (Figure 9) involves firstly mooring the iceberg offshore as discussed earlier (there is 180 m of water within 13 km of shore) and fragmenting it by one of the methods described above. The fragments are towed into a storage basin formed out of part of an inner bay and isolated from Saldanha Bay itself by a lock. Between the storage basin and the lagoon of Saldanha Bay (where the Sun heats the water to 20°C) there operates an ammonia turbine as used in ocean thermal energy conversion schemes. The warm water from the lagoon is pumped through a heat exchanger in which ammonia is evaporated; the vapor drives a turbine and is then condensed by the cold water in the storage basin. The warming effect of the ammonia vapor on the storage basin water enhances the melt rate of the iceberg fragments. DeMarle estimated that an iceberg of dimensions 900 m × 300 m × 200 m would yield power worth \$6.4 million at 3 cents/kWh and water worth \$2.8 million

at 6 cents/m³. These are attractive figures, and it is noteworthy that the power is worth more than the water. Such a scheme would be appropriate for irrigating and powering an agricultural complex with some settlement and industry involved. The value of the water would increase further if it were used as drinking or industrial water rather than for irrigation.

CONCLUSIONS

It appears that the Icetec concept may transform the economics of iceberg utilization. However, a high fixed investment would be needed to build the Icetec station, the storage basin, and the distribution network for water and power. For such a large fixed installation to be justifiable, the promoters must be sure that icebergs can be reliably delivered at acceptable cost to supply the system with its raw material. It is clear that the immediate need is for applied research and development in the areas of iceberg towing and iceberg processing. This will be expensive and will involve field work of which the logical first step is a full-scale tow of an instrumented iceberg to a coastal destination site. The data available so far suggest that if all the problems can be solved, then iceberg utilization can be economically attractive as well as beneficial to a world desperately short of water. However, the data also reveal a host of possible problems, any one of which could be fatal to the project. It remains to be seen whether any country or organization will find the balance of probabilities sufficiently positive to justify the major investment needed to take iceberg utilization from the research into the development phase.

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MANGANESE NODULE PROVINCES OF THE SOUTHERN OCEAN

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Manganese nodules known from bottom photographs and samples in dredges and cores occur in a belt as wide as 400 km on the seafloor around Antarctica. The majority of nodule fields appear to be of no economic potential in the foreseeable future, because the mean concentrations of Ni, Cu, and Co are low. However, we emphasize that study of Antarctica nodules is at the reconnaissance stage, and there could be large fields of high metal values yet undiscovered, as well as potential mine sites within known fields.

INTRODUCTION

Manganese nodules are known to occur around the periphery of Antarctica, in basins of varying depth and onto the lower flanks of adjoining ridges, rises, and plateaus. As in other occurrences throughout the world, the nodules are found in areas of relatively low sedimentation rate, and many seem to be found in localities where bottom currents move at considerable velocities. The seafloor shows nodule coverage ranging up to more than 60% and concentrations greater than 20 kg/m². Chemically, Antarctic nodules are not well characterized owing to the fact that they have not been sampled extensively and published analyses are rare.

Sources of information on Antarctic nodules are few. They include bottom photographs, chiefly taken during cruises of U.S.N.S. *Eltanin*, and dredge hauls and core materials retrieved by research vessels of several nations. Attempts to synthesize and evaluate the available data are hindered by a general lack of sufficient information on sampling methods, by the sporadic coverage represented by nodules taken or photographed, and by the differences in analytical accuracy and precision, as carried out in disparate laboratories. The present paper is limited to a generalized description of nodule occurrences in the Southern Ocean; nonetheless, it indicates areas that merit further investigation and prospecting for nodule resources.

MANGANESE NODULES AS A RESOURCE

As a potential source of important metals, manganese nodules must compete economically with other sources

in the costs of exploration, mining, transport, and processing. The viability of nodule mining in general appears to be approaching that of alternate sources of some metals such as nickeliferous (laterite), at least in fields of high metal values located near processing centers. For the Antarctic, distances from markets and the difficult weather conditions demand exceedingly high ore grades for any potential resource.

Characteristics required for commercial nodule mine sites in the central North Pacific [e.g., Archer, 1979] include the following: (1) Ni + Cu + Co grade greater than 2.25%, (2) bottom concentration greater than 10 kg/m², and (3) area of deposit at least equal to that of a circle of diameter 240 km. Various assumptions are included in all such calculations, but the figures above project the absolute minimum for any potential Antarctic mine site.

In the event a rich field were discovered in the Southern Ocean, additional development costs arising from the need to evaluate possible interference with the delicate and important environment might well make the project noncommercial.

DISTRIBUTION, COMPOSITION, AND DENSITY OF ANTARCTIC NODULES

The Southern Ocean is divided into six regions for the purpose of this paper (Figure 1). The regions correspond in general to oceanic basins lying between the Antarctic continental rise and elevated structures to the north. They are separated by various features as described below. In this discussion, nodules associated with ac-

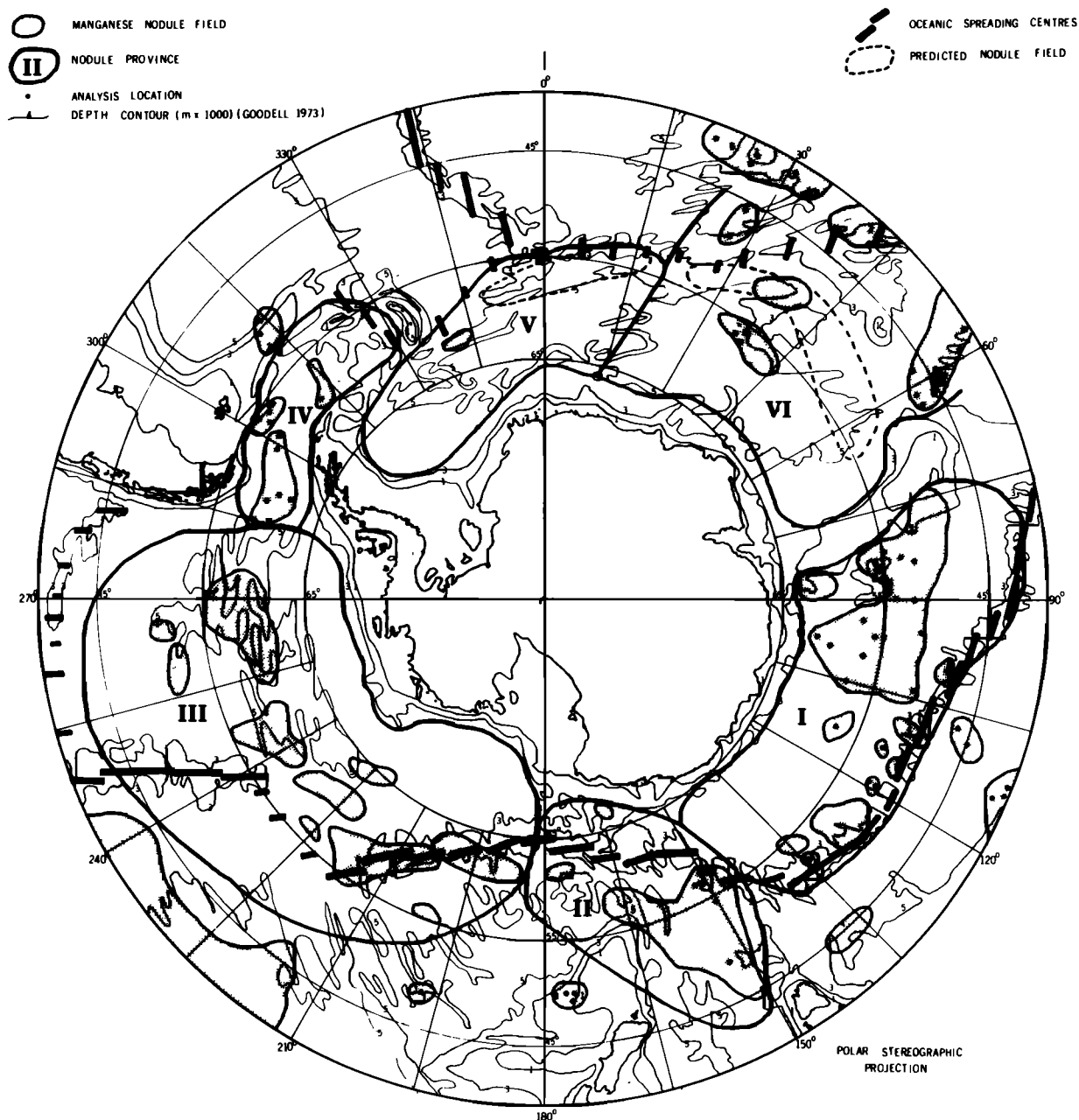


Fig. 1. Distribution of manganese nodule fields in the Southern Ocean. Adapted from Goodell [1973], Glasby [1976], Glasby and Lawrence [1974], Frazer *et al.* [1978], and Frazer and Wilson [1979].

tive spreading centers are not considered, as ridge crest nodules tend to display low concentrations of important metals [Bonatti *et al.*, 1972].

Area I

The first area is coincident with the deeper portions of the South Indian Basin, bounded on the east by the Southeast Indian Ridge and on the west by the Kerguelen Plateau. Nodules here (indicated by the dotted shading) are delineated largely by *Eltanin* bottom photographs.

Concentrations of nodules are limited to the western half of the basin except for small areas in the vicinity of the Australian-Antarctic Discordance, a broad zone of fracture zones crossing the ridge crest near 120°E longitude. Photographs show the likely existence of buried nodules scattered over other parts of the area, but the eastern half appears barren. Bottom roughness, another factor in evaluating mine sites, is very slight throughout the basin below about 3300-m water depth. Nodules are known only from depths greater than about 2300 m in this area.

TABLE 1. Abundance (Weight Percent) of Important Elements in Manganese Nodules by Province in the Southern Ocean

	Physiographic Province	Ni + Cu + Co	Mn/Fe	Mn	Fe	Co	Ni	Cu	No. of Analyses	No. of Sites
Area I	high	2.08	2.97	27.6	20.0	0.31	1.40	0.57	31	25
	low	0.11	0.18	2.2	5.3	0.03	0.03	0.02		
	mean	0.88	1.31	13.87	10.62	0.11	0.51	0.28		
Area II	high	1.76	3.48	21.5	24.4	0.73	0.92	0.20	16	16
	low	0.31	0.21	5.10	6.78	0.14	0.13	0.04		
	mean	0.82	1.10	13.29	14.92	0.28	0.38	0.11		
Area III	high	2.57	8.72	30.5	28.60	1.06	1.65	0.84	70	65
	low	0.16	0.13	1.00	3.50	0.01	0.07	0.07		
	mean	0.89	1.17	12.26	15.11	0.24	0.41	0.22		
Area IV	high	1.11	1.48	24.47	41.80	0.24	0.83	0.25	12	12
	low	0.09	0.24	8.65	12.73	0.02	0.02	0.06		
	mean	0.54	9.65	14.33	25.70	0.17	0.26	0.11		
Area V*	high									
	low									
	mean									
Area VI	high	1.94	3.02	24.40	25.10	0.37	1.43	0.46	32	16
	low	0.04	0.17	1.20	4.80	0.01	0.02	0.02		
	mean	0.78	1.05	12.61	12.48	0.14	0.45	0.19		

*No analyses are available for area V.

In composition, 31 analyses [Frazer and Wilson, 1979] indicate that nodule concentrations are generally low in the important metals (Ni + Cu + Co, and the average sum of these is 0.88%; Table 1). However, a nodule from the discordance area yielded a Ni + Cu + Co value of 2.08%. Nodules from area I are important only in their Co content, which attains moderate grade (up to 0.31%) near the Kerguelen Plateau. Nodule coverage on the seafloor ranges up to at least 30%.

On the north flank of the Southeast Indian Ridge, the Cape Leeuwin nodule field contains nodules of moderate to high grade in Ni [Frakes et al., 1978a, b; Frakes, 1982].

Area II

Area II is largely coincident with the southern part of the Tasman Basin but includes as well the lower portions of the South Tasman Rise and Macquarie Ridge. Data available for this region consist of bottom photographs and cores and dredges from cruises by *Eltanin* and other vessels. Nodule fields cover a broad area, and there are extensive areas of ferromanganese crust [Conolly and Payne, 1972; Frakes, 1975]. The density of manganiferous growths on the seafloor is thus very high, and these range to depths of less than 2000 m. On the basis of a model of modern deepwater circulation proposed by Gordon [1971], Conolly and Payne [1972] suggest that sedimentation rates are kept low by erosive Antarctic Bottom Water. This proposal is supported by the occurrence of strata as old as Gauss (~3.3 m.y.) at

the surface over much of area II [Watkins and Kennett, 1972].

Chemical analyses of 16 nodules from area II, reported by Glasby and Lawrence [1974] and Frazer and Wilson [1979], show that the region is characterized by relatively high values for Co (up to 0.73%) and low values for Ni and Cu (Table 1). Compared with other areas of manganese accumulation here and around the globe, area II is relatively small. Tonnages could be expected to be high, however, because of the high concentration of nodules on the bottom. As a potential mine site, area II has two advantages: the fairly high abundance of Co and close proximity to the industrialized centers of Tasmania.

Area III

The largest region of manganese accumulations in the Southern Ocean is a broad belt of deposits in the far south of the Pacific Ocean (Southeast Pacific Basin). Area III is arbitrarily separated from area IV in the Scotia Sea-South Atlantic, although the deposits are nearly continuous. Nodules floor the deepest parts of the Bellingshausen and Amundsen basins adjacent to the Antarctic continent and extend as well into fracture zones which cut the East Pacific Rise. They are particularly abundant in the region of the Eltanin Fracture Zone and in the fracture zones between about 140°W and 160°W longitude. Nodule deposits appear to be concentrated in the depth range between about 3000 m and the greatest depths encountered (>6000 m). Bottom

roughness is highly variable. Goodell [1973] considered that nodules here originated from the combined effects of submarine volcanic activity and strong bottom currents.

Over this enormous area, some 400 km wide on average by more than 3000 km long, Goodell *et al.* [1971] distinguished areas of concentrated nodules, areas of scattered nodules, and areas of crust development. Bottom coverage has been calculated from photograph data by Glasby [1976], who reports nodules in concentrations ranging up to 75% or more. From chemical analyses of 168 nodules, Goodell *et al.* indicate the following (arithmetic) mean values: Ni, 0.45%; Cu, 0.21%; and Co, 0.24%. These compare closely with mean values derived from 70 analyses published by Frazer *et al.* [1978] (see Table 1). In maps published by Glasby and Lawrence [1974], Ni and Cu appear to grade from lower abundances in the east to slightly higher values in the west of area III. Two analyses show high metal values (Ni + Cu + Co = 2.57 and 2.48%), although the extent of nodule fields of this grade in area III is not known.

Despite the enormous amounts of important metals represented by the deposits in area III, it is unlikely that the nodules will ever become a mineral source because the concentrations of Ni, Cu, and Co are too low.

Area IV

Area IV is the eastern continuation of area III, through Drake Passage, the Scotia Sea, and into the southwestern Atlantic. Data from Goodell [1973], Goodell *et al.* [1971], and Glasby [1976] are applicable and indicate bottom concentration as high as 75% and metal values similar to those of area III. Frazer *et al.* [1978] also indicate that nodules here do not differ significantly from those immediately to the west (Table 1). Ni values are somewhat higher (~0.80%) on the Falkland Ridge. Bottom roughness in area IV is sufficient to suggest that mining here would be difficult. In any case, metal values, including those for Co, are very low.

Area V

Very little information exists on manganese nodules in area V. However, the region would appear to have potential because of the presence of a sizeable deep basin (the Weddell Basin) and the fact that nodules occur farther north, near the African continental margin. Area V is bounded on the west by the South Sandwich Trench and on the north by the Atlantic-Indian Ridge. Area V is arbitrarily separated from area VI to the east, because of the known occurrence of nodules in area VI.

On the basis of what is known about other deep basins in high southern latitudes, it is logical to expect that abundant nodules will be present in this area and,

further, that they will contain low values for Ni, Cu, and Co. It should be pointed out, however, that area V, unlike other areas around Antarctica, is not known to be traversed by Antarctic Bottom Water and therefore may well differ in both nodule abundance and nodule chemistry.

Area VI

This region coincides roughly with the African-Antarctic Basin, bounded on the east by the Kerguelen Plateau and on the northwest by the Southwest Indian Ridge. To the northeast, the area is continuous with the Crozet Basin. The basin exceeds 5000-m water depth over much of its extent, and although only general bathymetric surveys exist, topography is probably mostly smooth, in view of its assumed Mesozoic age.

Thirty-two nodules from the southern Crozet Basin show analyses quite low in values of Ni, Cu, and Co concentration (Table 1). The few analyzed nodules from the African-Antarctic Basin also show similarly low values. Bottom coverage by nodules ranges up to at least 30%. As in most areas around Antarctica, neither bottom photographs nor chemical analyses are sufficiently numerous to allow for evaluation of the resource potential.

OVERVIEW OF NODULE POTENTIAL

The most striking feature of Antarctic manganese nodules is the enormous quantity of material that is known to exist. In effect, manganese nodules are present as a ring a few hundred kilometers wide that nearly circumscribes the Antarctic continent. Within the ring, nodule abundance is sufficient in many places to constitute a commercial deposit. Factors contributing to the formation of this series of deposits include the existence of several deep basins around the perimeter of Antarctica and the widespread occurrence of erosive and corrosive Antarctic Bottom Water.

Nodule chemistry is distinctive through this belt. Antarctic nodules typically display relatively low Mn/Fe ratios, generally less than 3.0. The Mn/Fe ratio appears to bear a direct relationship to the abundance of recognizable todorokite, the mineral which contains most of the economic metals. Because the ratios indicate relatively smaller quantities of todorokite than is present in other areas, the concentrations of Ni and Cu tend to be low. Cobalt concentrations are irregular, being mostly low but with intermittent high values. Cobalt tends to be higher with low Mn/Fe ratios, and this circumstance is surprising, but it is probably related to water depth. This influences the variation in Co in the lower part of the water column and also the mechanisms of concentration into the nodules. These characteristics of Antarctic nodules, at least in the well-known areas, are such as to

make the prospect for Antarctic nodule mining very remote.

There are two aspects of our present knowledge which are grossly inadequate for evaluating the resource potential of Antarctic nodules. First, large areas (such as area V) are virtually unexplored, and these could contain nodules of significantly differing chemistry. Second, within all areas of Antarctic nodules, the sampling density is so low that reserve-grade deposits could exist but remain undetected. To be properly tested for high-grade ores, a nodule field should be sampled on centers spaced at no more than 240 km. Thus there may be large important fields yet unexplored and there may be pockets of high-grade nodules that will come to light as investigations continue.

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ANTARCTIC LOGISTIC SUPPORT FOR THE EARTH SCIENCES

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This discussion of Antarctic logistics deals primarily with the operations of the U.S. Antarctic Program. The program makes use of all aspects of logistics which are employed throughout the Antarctic continent and surrounding oceans. In pursuing its research objectives, the U.S. program uses helicopters, Hercules (LC-130) ski-equipped aircraft, motor toboggans, tracked vehicles, hovercraft, research ships, and icebreakers. Large aircraft are universally used to transport personnel to and from Antarctica. Within Antarctica, the United States has also chosen to emphasize air transportation to carry scientific research to large parts of the continent. Logistic operations of this scale are extremely costly but are an inherent requirement of activities carried out in hostile and remote areas. Antarctic operations are not directly comparable to Arctic operations, because the north polar region has a much milder climate and inhabited centers are in relatively close proximity. In fact, Antarctic conditions are more closely comparable to those that will be encountered in future potential occupation and mining on the Moon and Mars. The U.S. approach to logistic support of Earth scientists has been remarkably successful in placing field parties of almost any size anywhere in Antarctica. These field parties have been able to work for periods of a few hours to an entire field season, with facilities and direct support that allow maximum time and effort for scientific research. Future efforts at commercial mineral evaluation and exploitation will need to look closely at the U.S. logistics effort as a possible pattern for their Antarctic operations.

INTRODUCTION

The United States and most nations which are consultative parties to the Antarctic Treaty support continuous, year-round, Earth sciences programs in Antarctica. Several other countries have Earth science programs on a periodic basis. This paper will center on these Earth science programs and the logistic support they receive. It is these aspects of Antarctic research that are giving us the background through which mineral potential, areas of mineralization, and mineral deposits can be found and evaluated. Field programs in the Earth sciences range from the station geophysics of a single coastal location, supported by a single annual visit of a resupply vessel, to complex integrated programs, consisting of many aspects of geology, geophysics, and cartography and ranging over much of the continent.

The ultimate goals of the U.S. support of Earth sciences research in Antarctica are to determine the

geology, geologic history, and mineral potential of Antarctica, in the broadest sense. To accomplish these goals, every attempt has been made to develop logistic capabilities that are able to place Earth scientists anywhere in Antarctica, efficiently, safely, and productively. Over the last 30 years, most of the areas in which bedrock is exposed have been investigated in at least reconnaissance fashion. Terrestrial Earth sciences of all types are supported from permanent bases by over-snow traverses with tracked vehicles, by fixed-wing aircraft and helicopters, and from temporary inland camps put in place and supplied only by aircraft. A wide variety of mobile bases also support Earth science research. Marine Earth sciences are conducted from aircraft, supply ships, research ships, and icebreakers. These often involve remote sensing of gravity, magnetics, reflection seismic surveys, and marine geology. They also include direct observations such as dredging and coring. Other marine Earth science research is

carried out from tracked vehicles located on fast sea ice (sea ice anchored to the shore).

The U.S. approach to logistic support of Earth scientists has been remarkably successful in placing field parties of almost any size almost anywhere in Antarctica. These field parties have been able to work for periods of a few hours to an entire field season, with facilities and direct support that allow maximum time and effort for scientific research [Turner, 1962, 1979]. Future efforts at commercial mineral evaluation and exploitation will need to look closely at the U.S. logistics effort as a possible pattern for Antarctic operations.

Mineral exploration and mining in Antarctica will face extreme problems in climate, transportation, and personnel [Spletstoesser, 1976]. The experience gained over the last half century in Antarctica, particularly by the larger expeditions mounted by the United States and the USSR, will be valuable background on which to build. Actual exploration and mining experience in the Arctic will also point the way toward solving the problems that will be faced in the Antarctic. Successful and profitable mining and drilling operations have been carried out for many years under the very adverse conditions of northern Siberia, the North Slope of Alaska, the Arctic Islands of Canada, Greenland, Svalbard, northern Sweden, and the North Sea. However, the most useful source of technological thinking for conditions comparable to those to be found in Antarctica are in the many planning documents prepared by the National Aeronautics and Space Administration for future occupation and mining on the Moon and Mars.

UNITED STATES ANTARCTIC PROGRAM

Much of the geological and geophysical research on the continent during the International Geophysical Year (IGY) and early post-IGY periods was supported by very long over-snow traverses with tracked vehicles. The present trend is increasingly toward the establishment of temporary field camps that operate from 1 day to several months, with short traverses radiating outward from the camp. These camps are placed in remote areas of the field and supported by fixed-wing, ski-equipped aircraft (LC-130's) and/or by helicopter. The United States supports both research and logistics for field projects in Antarctica, all of which are administered through the U.S. National Science Foundation (NSF), with line item funds appropriated by the U.S. Congress. Logistic operations are carried out through contracts by NSF with the U.S. Navy, U.S. Coast Guard, a private contractor (ITT Antarctic Services, Inc., in 1989), and the U.S. Air Force. During the 1989 Fiscal Year (1988–1989), U.S. funds available for direct support of the Antarctic Program were \$141,000,000. Of this, \$15,500,000 were for direct grants for science research, and \$125,500,000 were for logistic support for

these science projects. This high percentage of total program funding for logistics is the result of the high cost of extensive field efforts in Antarctica, especially inland research. Earth science projects supported by the United States are conducted at stations, aboard ships, and by air in virtually any part of the continent, with individual field parties ranging in size from 2 persons to as many as 40 persons.

An extensive, multimode logistic support system has enabled the United States to support a versatile program by (1) maximizing air transportation of people, equipment, and supplies to and within Antarctica and (2) using modern, efficient, and powerful icebreakers and ice-strengthened cargo vessels to transport heavy and bulky equipment, supplies, and fuel to the coastal stations of Antarctica. For example, the United States uses icebreakers to carry most of the heavy supplies, equipment, and fuel to Palmer Station, in the Antarctic Peninsula [National Science Foundation, 1980]. Some lighter supplies and equipment, as well as most of the personnel, are taken to and from Palmer Station by the *Polar Duke*, a research vessel capable of breaking moderate ice. The vessel also serves as an ocean-based field extension of research at Palmer Station.

SHIP OPERATIONS

Since 1947 when the United States Coast Guard icebreaker *Northwind* (under command of the U.S. Navy) escorted Rear Admiral Byrd's fleet into the Bay of Whales during Operation Highjump, and the austral summer of 1956–1957 when *Northwind* and *Westwind* escorted supply ships into McMurdo Sound for the International Geophysical Year, U.S. Coast Guard icebreakers have played a major role both in Antarctic logistics and direct scientific support. The U.S. polar icebreaker fleet at one time numbered eight ships, but it has now been reduced to two, USCGC *Polar Sea* (WAGB-11), and USCGC *Polar Star* (WAGB-10). These Polar Class ships are the world's most powerful nonnuclear icebreakers and are primarily used as escort and logistics ships, but they have a significant scientific support capability, which is in the process of being considerably improved.

The role that the icebreakers play in support of the U.S. Antarctic Program is twofold: logistics and direct scientific support. A major logistics mission is to break the shipping channel through the fast ice of McMurdo Sound into Winter Quarters Bay for the annual bulk resupply ships coming to McMurdo Station. The second major logistical mission is the resupply of Palmer Station on the Antarctic Peninsula. Other logistical tasking not related to McMurdo Station or Palmer Station is common and occurs along the coast of the continent. For direct scientific support, the icebreakers serve as research and data-collecting platforms for investigators



Fig. 1. U.S. Coast Guard Polar Class icebreaker in Antarctic waters near the Antarctic Peninsula. One of the Sikorsky H-52 helicopters is visible on the flight deck of the *Polar Sea*.

conducting research in a wide variety of disciplines under the aegis of the U.S. Antarctic Research Program.

The Polar Class icebreakers (Figure 1) are 121.6 m in length overall, with a maximum breadth of 25.5 m and a mean draft of approximately 9.7 m at a displacement of 11,990 metric tons. They have three 4.9-m-diameter controllable pitch propellers and are powered by one or two diesel generators providing up to 6000 horsepower per shaft in diesel electric mode, or by one gas turbine per shaft which develops a maximum of 25,000 horsepower. These ships can carry 3898 metric tons of diesel fuel, giving them a maximum cruising range of approximately 45,000 km at a speed of 13 knots. The two Polar Class ships are Class 6 icebreakers, capable of breaking 1.8-m (6-feet) thick ice at a continuous speed of 3 knots. The ship's allowance of 14 officers and 127 enlisted personnel is augmented by an aviation detachment of 4 officers and 10 enlisted when the 2 helicopters are embarked. The Coast Guard has upgraded the embarked helicopters from the aging single-engine Sikorsky H-52 to the modern, faster twin-engine HH-65 Aerospatiale Dolphin helicopter.

The Polar Class icebreaker's logistics outfit consists of cargo holds, some refrigerated stowage, a deck stowage area, cargo-handling cranes, and boats. The upper hold has a capacity of about 116 m³ (or 93 metric tons) of cargo. The lower hold can carry 82 m³ (or 66 metric tons) of cargo. Approximately 255 m³ of freezer space in commissary stores could be made available for some types of scientific cargo. The ships have three cargo cranes: a 3-ton capacity crane forward, primarily for handling commissary stores, and two 15-ton capacity cranes aft which are used to handle the larger ship's boats and to handle cargo to or from the two aft cargo holds. The ships have two 12-m Landing Craft Vehicle

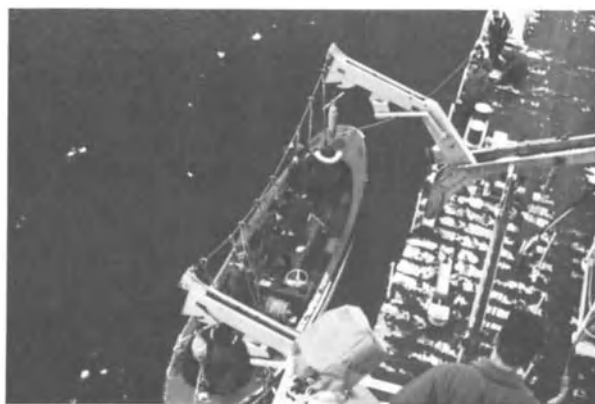


Fig. 2. A Landing Craft Vehicle Personnel (LCVP) has been lowered by crane to take a science party to shore.

Personnel (LCVP) which can carry a load of 4 tons (Figure 2). These are outstanding logistics craft and, with the bow ramp, are well able to transport equipment and personnel to undeveloped landings. The ships have an enclosed 12-m fiberglass Arctic Survey Boat (ASB) with a small galley, 4 berths, head, and cabin working area. The ASB has a separate diesel generator capable of producing electrical power of 110 V ac to power the boats' navigational electronics and necessary scientific equipment. Another craft, a 4.5-m inflatable boat with a 30-horsepower outboard engine, is available for carrying light loads. The ship's 8-m Motor Surf Boat is primarily used as the ready boat for emergencies but is also available to carry up to 12 personnel in addition to the boat crew. The Aerospatiale HH-65A helicopters have a load capacity of approximately 230 kg, or 2 or 3 passengers, and a range of 900 km. For shorter distances (15–25 km) they may carry roughly 550 kg. They can carry larger-sized loads and hazardous cargos in sling loads beneath the helicopter.

The Polar Class icebreakers have installed scientific equipment which is used by ship's personnel in the conduct of routine oceanographic and meteorological observations. Equipment used for the routine observation programs include a RAYFAX machine connected to a radio receiver, an automatic picture transmission (APT) satellite receiver and printer, a shipboard environmental data acquisition system (SEAS III) connected to an expendable bathythermograph (XBT) system, and a line scan recorder (precision depth recorder) which is used in conjunction with the installed fathometer/recorder. The major oceanographic equipment includes two oceanographic winches, one with 6000 m of 0.25-in. center conductor cable and the other with 6000 m of stainless steel hydrographic cable and an extendable oceanographic boom for casts and net tows.

The information gained is available to scientific parties on board. The ships have a complement of four

marine science technicians (MSTs) who not only conduct the ship's daily routine meteorological and oceanographic observations, but also operate winches and otherwise assist field parties. Generally, the ship's crew is one of the most important logistic assets. In addition to their routine duties of operating the ship, its boats, and handling cargo, they have repeatedly shown their ability to support a variety of projects by making emergency repairs to vital project research equipment.

For science spaces the ships presently have the following: a chemical/dry laboratory, a wet laboratory/winch room, a meteorological laboratory, and a science library. The chemical/dry laboratory has approximately 22 m² of deck space, plus laboratory facilities. The wet laboratory/winch room is located a few feet from the dry lab. The meteorological laboratory is manned by the MSTs full time when the ship is under way. The ships can provide berthing for 18 to 20 field party personnel. They also have the capability of installing additional vans on the weather decks for the use of scientific parties. Two 2.1-m by 4.1-m science vans can be secured to the decks on the port and starboard sides. In addition to installed laboratory facilities, heating/air conditioning, and lighting, these vans are connected to the ship's electrical, freshwater and seawater, and telephone systems.

The Polar Class icebreakers are now undergoing modifications to the installed scientific suite to substantially improve the capability to support embarked field parties. The coring modification was installed in *Polar Star* in 1988, and the oceanographic modification is scheduled to be installed in *Polar Sea* in 1989. In 1990–1991 the ships are scheduled to receive modifications including a coring/trauling winch, a J-frame, winch operator control booth, a 3.5-kHz echo sounding system, an acoustic Doppler speed log, a TV monitoring system for science operations, and an overhead gantry/J-frame system which will allow handling rosette samplers up to 2.4 m in diameter from over the side into the enlarged wet lab. The existing meteorological laboratory is to be enlarged and converted into a computer room with space for the ship's installed Coast Guard Standard Workstation System and computers brought aboard by the field parties. This modification also includes the construction of a wet laboratory to be located on the starboard side of the fantail, which will have doors and racks to enable cores to be moved in from the weather.

Brief descriptions of typical recent logistics and science support projects will illustrate the flexibility of these ships. The annual resupply of Palmer Station is, typically, the largest cargo-handling assignment that the Polar Class ships have in Antarctica. Cargo for Palmer Station is loaded at Port Hueneme, California. The cargo load varies somewhat from year to year but is generally over 270 metric tons. For the 1983–1984 field

season, cargo was 370 metric tons, filling both holds and carrying over to deck cargo. Fuel for Palmer Station is taken aboard with the ship's fuel. The ship will normally proceed via Punta Arenas, Chile, where she will take additional fuel and embark the summer season scientific party and support personnel for Palmer Station. The quantity of fuel provided Palmer Station varies, but it generally ranges from 332 to 473 metric tons. Cargo is taken ashore in the LCVPs also. The operation at Palmer Station is very weather dependent, and winds of 50 knots or more can come up in as little as 25 min. Ice in the harbor sometimes complicates the offload.

Sometimes the ships perform less routine logistics tasks such as removing contaminated waste oil from the Hallett Station site and refueling the Navy auxiliary helicopter field near Marble Point during the 1988–1989 season. Both jobs were technically uncomplicated, but neither could have been done by a ship which did not have a significant icebreaking capability. At Cape Hallett, after closing the beach and offloading hoses and pumps directly onto the sea ice, just over 144 metric tons of oil were recovered in 8 hours, including pumping and handling equipment.

The Marble Point Air Facility is an airstrip/helicopter launch pad and fuel depot for U.S. helicopters supporting field parties in the dry valleys and other sites west of McMurdo Sound. The depot has been refueled by several methods. Infrequently, the Navy UH-1N helicopters have hauled some fuel to Marble Point by external slingload from McMurdo. Most seasons have seen seven to nine sledge traverses across the sea ice early in the summer. During one recent season, however, it became apparent that the fuel supply was not sufficient to meet helicopter requirements for the rest of the field season, and the sea ice by then was too weak to support another traverse. The icebreaker, carrying hose and pumps, proceeded to the edge of the fast ice, 6.5 km from the beach. The *Polar Sea* broke through the first 3.2 km of consolidated first-year ice in approximately 2 hours, but the remaining 3.3 km took 11 hours of backing and ramming on two gas turbines. After transferring over 118 metric tons of fuel to the depot, the return to the fast ice edge was accomplished in approximately 6 hours. While hove to for the fueling job, the crew completed a sounding program of the bay with over 30 data points, the first since 1957. Finally, the ship became a platform of opportunity for Navy helicopters carrying several tons of refuse and retrograde cargo from several field sites in the area.

During one recent Antarctic deployment, in addition to the channel breaking and supply ship escort, one icebreaker supported three science cruises. The first cruise supported three projects, and the second and third each supported five projects. The second and third cruises were interesting owing to the diversity among the projects. Very briefly, the Earth sciences projects

supported were as follows: (1) Antarctic surveying and mapping (two field engineers, established five geodetic control points using satellite geocoders, and several conventional surveys ranging from Inexpressible Island to Siple Island to Anvers Island); (2) Cenozoic glacial history of Antarctica (three investigators, visits to Siple Island and Livingston Island, and helicopter surveys along Gerlache Strait); (3) resource and radioactivity survey in Antarctica by gamma ray spectrometry (two investigators, visits to Siple Island, Deception Island, and other sites in the Antarctic Peninsula and Gerlache Strait area); (4) volcanic geology of Marie Byrd Land and its relationship to glacial and tectonic history in West Antarctica (four investigators, visits to Siple Island and Deception Island); (5) Ross Sea heat flux experiment (four investigators, oceanographic sections in the Ross Sea along the ice shelf and in the vicinity of Cape Hallett and Terra Nova Bay); (6) Ross Sea heat flux experiment (two investigators, deployed 10 current meter arrays in the vicinity of Terra Nova Bay and the edge of the Ross Ice Shelf); and (7) Antarctic automated weather stations (two investigators, serviced the automated weather station on Franklin Island, and established new stations on Inexpressible Island and on the Ross Ice Shelf near 172°30'W).

In addition to the U.S. Coast Guard icebreakers, the National Science Foundation makes use of a number of smaller research vessels [*National Science Foundation*, 1988]. Several ships of the U.S. academic fleet (*Melville*, *Knorr*, *Alpha Helix*) have worked in ice-free Antarctic waters as well as the deep-sea drilling ships *Glomar Challenger* and *JOIDES Resolution*. Since 1985 the 67-m ice-strengthened research vessel *Polar Duke* has been chartered by NSF through its private contractor for use in the Southern Ocean. Its main operational area is near the Antarctic Peninsula, the Drake Passage, and the Scotia Sea. The ship has a crew of 14 and can accommodate 26 science personnel. The ship has the icebreaker classification IAA, is powered by two diesel engines, each delivering 2250 horsepower, and cruises in open water at 22 km/h (12 knots). The *Polar Duke* has an endurance of 90 days and has major science equipment on board, including four laboratories (84 m²), winches, a piston corer, single-channel seismic gear, and other equipment to support science projects in marine biology, physical and chemical oceanography, and marine geology and geophysics.

Each year, when the sea ice channel has been broken by the icebreakers during late January, two ice-strengthened supply ships reach Winter Quarters Bay at McMurdo Station, but both need the assistance of an icebreaker for escort. The ice-strengthened tanker delivers approximately 20,000,000 liters of diesel fuel (DFA), jet fuel (JP-4), and gasoline to McMurdo Station. The tanker is operated under contract to the Military Sealift Command [*National Science Founda-*

tion, 1988] and is an ice-strengthened container ship. It delivers cargo for use at McMurdo Station and South Pole Station.

AIR SUPPORT

The following are some of the reasons the United States has chosen to emphasize air transportation to and within Antarctica:

1. To carry scientific research to large parts of the continent. This wide-ranging distribution of scientific endeavor also serves to uphold national policy, and the Antarctic Treaty, which stipulates that the entire continent is open to research.

2. To allow broad scientific comparisons and correlations from one part of Antarctica to another.

3. To minimize the time needed by Earth scientists from academic institutions and government agencies, who are not professional polar scientists, to conduct research in Antarctica. The use of aircraft illustrates that in many ways, the most precious commodity in Antarctic research is time. Time spent in transit detracts from time spent in research.

4. In order to support Earth scientists whose experience under severe field conditions may be quite limited. The U.S. goal is to make all Antarctic research areas accessible to any reasonably healthy scientist, with maximum feasible safety.

To carry out these goals, the National Science Foundation owns and makes use of 4-engine turboprop transport airplanes for long-range air operations (cruising speed 500 km/h, or 275 knots) across the Antarctic continent as well as for air service between McMurdo Station and Christchurch, New Zealand. Christchurch functions as the advanced land support base with full facilities for heavy aircraft but is located at a distance of 3860 km north of McMurdo Sound.

The U.S. Navy Antarctic Development Squadron VXE-6 operates the seven Hercules LC-130s [*Fowler*, 1988], which are modified C-130 cargo planes with a combination of wheel and ski landing gear (Figure 3). Owing to its dual landing gear and high payload, the airplane has proven to be extremely versatile, particularly for open-field landings without any prepared runways. The plane has a cargo area of 12 × 3 × 3 m and can carry as much as 12,200 kg (27,000 pounds) of cargo and/or people, for example, to the South Pole from McMurdo (728 nautical miles) and return without refueling [*National Science Foundation*, 1988]. In some cases the payload might be reduced by almost one half of its normal capacity if the takeoff conditions are characterized by soft and deep snow. Under particularly adverse conditions eight jet-assisted takeoff (JATO) bottles, four bottles on each side of the fuselage, can aid in the takeoff procedure.

Although many of the available flight hours are



Fig. 3. The ski-equipped Hercules LC-130s are operated by the U.S. Navy (VXE-6 Antarctic Development Squadron) for the National Science Foundation.



Fig. 4. A U.S. Air Force Starlifter C-141 has landed on the sea ice at McMurdo Station.

needed for refueling flights to South Pole Station, some years are characterized by a high degree of open-field work [Fisher, 1985]. Some of the Earth science projects requiring open-field landings were (1) geological studies at the Jones Mountains, Ellsworth Mountains, and Mount Smart, (2) search for meteorites at the Allan Hills, (3) volcanic research at Mount Takahe, and (4) stratigraphic evolution and tectonic setting research, Ross Sequence, Transantarctic Mountains, Nimrod Glacier, and Starshot Glacier. At the Starshot Glacier a small tent camp had to be relocated, and in this attempt one LC-130 was trapped in a crevasse and severely damaged. However, the aircraft was repaired and flown from the site within 2 weeks. The main U.S. supply and air transport base in Antarctica is at Williams Field, near McMurdo Station, which has snow runway on the surface of the Ross Ice Shelf. Another runway, on the annual sea ice at McMurdo Sound, is generally used from October through December, before the sea ice becomes too weak to support safely large aircraft with wheeled landing gear only. This runway, having a total length of about 3000 m, is prepared each year by Navy "Seabees" (Naval Construction Battalion). The annual sea ice has a thickness of about 4 to 7 m and is able to support C-141 aircraft of over 129,371-kg gross weight (Figure 4). The arrival of this aircraft, the "Starlifter" operated by the U.S. Air Force, signals the beginning of the cargo season, fulfilling large early season passenger and cargo requirements [Harler, 1985]. In October 1989 the sea ice runway proved capable of supporting the C-5B Galaxy airplane carrying a load of 76,000 kg [National Science Foundation, 1989]. These flights of wheeled aircraft are augmented by wheeled C-130s in cooperation with the Royal New Zealand Air Force and the New Zealand Antarctic Research Program. The earliest flights to Antarctica at McMurdo Station take place in August. At this time, daylight hours are limited,

and very low temperatures prevail in combination with high winds. Therefore these special winter flights (WIN-FLY) are particularly hazardous [Mendicino, 1987], but they provide the personnel to prepare the ice runway and McMurdo Station for the opening of the austral summer season in October.

Helicopters are the primary transport for field parties from McMurdo Station to the Transantarctic Mountains, particularly the dry valleys (ice-free valleys) of southern Victoria Land. Six or seven U.S. Navy UH-1N helicopters are used in the U.S. Antarctic Program during the austral summer. This aircraft is a twin-engine turbine type with each engine capable of delivering 900 shaft horsepower. Average fuel consumption at cruise speed (185 km/h, or 100 knots) is approximately 274 kg/h (600 pounds/h). The standard fuel capacity of 639 kg (1400 pounds) can be augmented by the use of an auxiliary fuel bladder with a capacity of 411 kg (900 pounds). Total flight time can thereby be extended to nearly 4 hours. The U.S. Navy recommends 730 kg (1600 pounds) as net useful load or up to 5 passengers. Using an external cargo sling, the UH-1N can carry as much as 1400 kg (3000 pounds) [National Science Foundation, 1988].

The twin-engine model (UH-1N) has been flown in the U.S. Antarctic Program by U.S. Navy pilots (VXE-6) since the 1971-1972 field season. The two engines are designed for high performance (service ceiling 4267 m), low maintenance, and a high payload-to-weight ratio, in addition to the increased safety factor of the two engines [Spletstoeser *et al.*, 1982]. This aircraft, as shown in Figure 5, has provided geologic field parties with extremely versatile transport to fulfill mainly two tasks: establishing small field camps in the Transantarctic Mountains or on top of the active volcano Mount Erebus (elevation 3794 m) and serving as a surveying platform for radiometric equipment or observations of



Fig. 5. A U.S. Navy UH-1N helicopter in mountainous terrain in the Transantarctic Mountains in support of a science party.

glacial remnant features on the upper levels of the Transantarctic Mountains.

PERMANENT STATIONS AND FIELD CAMPS

The United States and many other nations support continuous, year-round, Earth sciences programs in Antarctica. Field programs in the Earth sciences range from the station geophysics of a single coastal location, supported by a single annual visit by a resupply vessel, to the complex transcontinental integrated programs of the United States and the USSR. Of the 38 Antarctic Treaty nations, 16 nations maintain year-round stations at over 30 locations south of 60°S along the coast [National Science Foundation, 1988; Fowler, 1988]. Most of these are accessible only by ship [Central Intelligence Agency, 1978]. In addition, there are 2 inland stations on the polar ice sheet operated year round: (1) Vostok Station (USSR) at the south geomagnetic pole, elevation about 3500 m, and (2) Amundsen-Scott Station (U.S.), at the geographic South Pole, elevation about 2900 m. A third inland station, Siple Station, in Ellsworth Land, was operated by the United States for about 2 decades but has recently been closed. Vostok Station is almost completely supplied by surface traverse tractor trains from Mirny Station on the coast, although the Soviets also use wheeled aircraft with oversize tires for supply flights to Vostok. In contrast, the Amundsen-Scott South Pole Station [National Science Foundation, 1984] is supplied entirely by LC-130 aircraft (Figure 6) from McMurdo Station, on Ross Island [National Science Foundation, 1983].

The maintenance cost of the rather modest Amundsen-Scott base at the South Pole (Figure 7) with a wintering-over population of about 20 persons consumes approximately half of the logistic funds available to the U.S. Antarctic Program. This is in addition to the original cost of the installation. The dome at South Pole



Fig. 6. A ski-equipped Hercules C-130 in front of the Amundsen-Scott South Pole Station.

was constructed in 1975 and has proved to be stable and safe with an estimated life expectancy of 30–40 years. The earlier South Pole Station used under-snow construction of elongated rectangular buildings in trenches [Splettstoesser and Bresnahan, 1988]. These subsurface buildings were only usable for about 10 years because of the weight of snow accumulation on top of them. The present geodesic dome was designed to minimize snow accumulation on and around it and to allow mechanical removal of lee-side snow drifts. Logistic supply and personnel transportation into and out of the U.S. station at South Pole are entirely by air. Much of the operational services at the station are provided by a private contractor.

McMurdo Station on Ross Island, at 77°51'S (Figure 8), due south of New Zealand on Ross Island, relies largely on late season cargo ships for bulk resupply in coordination with Coast Guard icebreakers. Most of the personnel for McMurdo and neighboring New Zealand Scott Base, as well as much of the scientific equipment and fresh food, are carried in by C-130 and C-141



Fig. 7. View of living quarters under the geodesic dome at Amundsen-Scott South Pole Station.



Fig. 8. View of "downtown" McMurdo Station during a blizzard.

aircraft staging from New Zealand. The wheeled U.S. Air Force C-141 aircraft operate through early December on the annual ice runway as do Royal New Zealand Air Force C-130 aircraft. Ski-equipped LC-130 aircraft operate throughout the summer season using the skiway at Williams Field starting in early December when the annual ice runway normally becomes unusable because of thawing.

The locations of most coastal stations have been chosen to allow access by supply ships. Almost all station locations in coastal Antarctica require ice-strengthened ships or, in some cases, icebreakers. A few coastal stations are so difficult to reach during some years that resupply must be done by cargo helicopters from icebreakers lying outside zones of extremely heavy sea ice. All stations carry supplies for at least 2 years, in case ocean conditions prevent resupply during the summer. There are very few remaining coastal locations that can be approached by ships or that can allow discharge of cargo. Almost all desirable locations are presently occupied by national research stations. Locations of many of the present stations do not allow space for landing fields for either wheeled or ski-equipped aircraft. Access to the interior from some of the coastal stations is not possible by motorized vehicle transport. Thus it can be seen that any development or mining operations in coastal Antarctica will be dependent upon access to coastal locations where resupply by ship or air and access to the interior are possible. If such a location can be found that is presently unoccupied, a supply base will have to be built from scratch. Otherwise, access and cooperation will need to be obtained from an already existing national base. Increasingly, Earth scientists are being placed in isolated field locations as part of large integrated programs for periods of up to 2 months. This is accomplished by constructing large temporary field camps [National Science Foundation, 1985; Elliot *et al.*, 1986]. These camps are trans-



Fig. 9. Field party with Scott tents and motor toboggans, transported to the field by LC-130 aircraft. Typical of the very successful open field landing operations of these aircraft on glacial terrain in the Transantarctic Mountains.

ported by Hercules aircraft and constructed by the logistics contractor. A detachment of helicopters can self deploy or be air transported to the camp by LC-130 and act as local transportation for scientists to areas of specific research within a radius of about 200 km. Summaries of the use of turbine helicopters for the support of remote field camps are given by *Rutford and Smith* [1966] and *Spletstoeser* [1985].

Helicopter operations at these temporary camps usually include reconnaissance, close support of field parties, put-in and pickup of field parties that plan to remain in the field for extended lengths of time. Such small field parties put up tent camps and do their field work on foot or make use of motor toboggan transport (Figure 9). The large temporary camps consist of Jamesway buildings, which are constructed from a series of wood arches covered by padded cloth (Figure 10). They can be made in any length desired. Each camp has included five Jamesway buildings, ranging from 12 m to 22 m in length, the most sophisticated of which is a cooking/dining facility and adjacent toilet/bathing area with hot and cold running water. All camp components are dismantled and returned to McMurdo Station at the end of the field season, usually in late January. A view of a typical camp is shown in Figure 11 located in Marie Byrd Land, partly snow covered by a blizzard which lasted several days.

Normal camp populations have averaged about 40 scientists and about 25 support personnel. As many as 60 scientists have used these camps in a single season. The first remote science camp built in Antarctica for the exclusive purpose of providing a base for helicopter operations in a U.S. field program was in the 1963–1964 austral field season in the Ellsworth Mountains. Beginning with the 1977–1978 austral season, a more elaborate style of construction and accommodation was in-



Fig. 10a. Jamesway construction.



Fig. 10b. Complete Jamesway buildings.



Fig. 11. Typical remote camp making use of Jamesway structures. This camp was located in Marie Byrd Land, West Antarctica, with a detachment of three UH-1N helicopters.

stituted with the program carried out at the camp in Marie Byrd Land and at other locations in succeeding years: Darwin Glacier, 1978–1979; Ellsworth Mountains, 1979–1980 [Splettstoesser and Webers, 1980; Splettstoesser and Turner, 1982; Splettstoesser *et al.*, 1982]; northern Victoria Land, 1981–1982 [Stump *et al.*, 1982]; and Beardmore Glacier, 1985–1986 [Elliot *et al.*, 1986]. Each of these camps has taken 10 to 14 days to build and has involved from 7 to 11 LC-130 aircraft flights for a total cargo weight of 45,000 to 55,000 kg. About 500 to 820 helicopter hours [Reed, 1986] have been flown in direct support of scientific projects in each of the field camp seasons.

Successful operation of remote camps requires careful advanced planning that must take into account anticipated personnel capacity, food supplies, and aviation fuel storage facilities. Maintenance of communication channels is particularly important for operational and safety reasons. Thus far, remote camps have relied upon shortwave radio for almost all communications, but the possibility of using polar-orbiting satellites is now being actively explored. Facilities are now in operation at South Pole Station which permit data transmission by satellite links to McMurdo Station and home institutions in the United States [Comberiate, 1985].

A wide variety of vehicles are used for ground transport at stations and remote camps. Tracked vehicles are especially suitable for transport over hard snow and ice surfaces. Motor toboggans are used extensively for transport of personnel, supplies, and equipment. For heavier or larger loads, Snow-Cats, Trackmasters, and Sprytes are used. For moving heavy objects and for excavation, Caterpillar tractors are usually required and are available at all stations and some remote camps. Most recently, hovercraft have been tested and have proven to be extremely efficient for many types of

operations. They are much faster than most other types of ground vehicles and are virtually unaffected by snow surface conditions. Although unable to negotiate steep grades and unsuited to pulling sleds, they can transport substantial loads. The recently introduced Griffin 1500 air cushion vehicle in the U.S. Antarctic Program [Wilkniss, 1988] has a rated capacity of 1.5 metric tonnes (3300 pounds). The hovercraft, shown in Figure 12, is powered by a 190-horsepower, turbocharged diesel. Fuel consumption is between 4 and 6 gallons per hour at speeds of about 74 km/h (40 knots).

DISCUSSION AND CONCLUSIONS

The weather in parts of Antarctica is the most extreme on Earth. This is where record low temperatures, the highest average wind velocities, and the longest sustained periods without sunlight under terrestrial conditions are found. Much of the continent is covered by thick glacial ice that will be an uneconomic overburden to at least 90% of the potential mineral deposits. All of these factors work to the detriment of equipment and people. There are three major climatic zones in Antarctica: (1) the frigid interior, (2) the stormy coastal zone, and (3) the somewhat milder but still difficult Antarctic Peninsula. Minimum temperatures recorded in the interior are in the -85°C to -90°C range (world's record low temperature of -89.2°C was at Vostok Station on July 21, 1983). Annual average temperature in the interior is approximately -50°C . Maximum summer temperatures in the interior above 0°C are almost never recorded. Winds are generally light and precipitation in the form of snow is equivalent to about 10 cm of moisture. No melting of snow occurs, and buildup of the icecap is balanced by the slow outward flow of the ice toward the coast. Any installation constructed below the snow surface in the interior thus has a constant ambient temperature of about -50°C . Installations built on the surface have the advantage of somewhat warmer summer air temperatures and solar heat input but must counteract the extreme low winter temperatures and even lower wind chill factors.

Work outside during the summer in the interior of the continent is difficult, inefficient, and dangerous. Travel for short distances on foot and by vehicle for longer distances to outlying laboratories and work areas is feasible under strict safety rules, except during major storms. Winter work outside in the same areas is almost impossible. Any extensive year-round drilling or mining operation anywhere in Antarctica will require an artificially maintained environment. The geodesic dome constructed at the South Pole by the United States is an example of what might be used to enclose and cover any drilling, mining, milling, or concentrating operation in Antarctica. Thus far, all aircraft landing in the interior must be ski equipped to use the soft-snow runways on



Fig. 12. Griffin 1500 air cushion vehicle in operation on the Ross Ice Shelf. In this view the hovercraft is approaching a tracked vehicle.

the icecap. However, some areas of blue ice exist scattered across the Antarctic ice sheet, mostly in high-wind locations near mountain ranges, and these are being actively explored as landing surfaces for heavy, wheeled aircraft [New Zealand Antarctic Society, 1989].

The stark absence of any living plant material can act as an insurmountable emotional burden to many individuals. The psychological and medical problems faced by winter-over crews, particularly at the inland stations, should be looked at carefully in choosing individuals. The experiences along these lines by the New Zealand Antarctic Division, for example, have been discussed by Taylor [1988]. These same factors should also be considered in planning for the size and makeup of the crews at individual installations. Experience in the U.S. program indicates that there should be a minimum of three persons at a station and that three to 20 persons are usually the viable, stable groups. Any installation with more than about 20 persons tends to grow in number over a period of years through bureaucratic necessity.

In spite of the difficulties outlined above, each of the individual science projects has contributed to the evaluation of some part of the continent for its mineral potential. Several projects have been specifically aimed at investigating mineralization or in searching for mineral deposits. However, only one metal-bearing province has been shown to have metallic concentrations that, if they had been found on some other continent,

would warrant consideration for exploitation. This is the region of rare-Earth and radioactive elements of northern and southern Victoria Land, reported by Zeller *et al.* [this volume]. Several other investigators have indicated areas where the mineral potential is great enough to warrant specific search for mineral deposits in the future. Among these are the discovery of copper-bearing intrusions at the base of the Antarctic Peninsula by the U.S. Geological Survey [Rowley *et al.*, 1977], widespread mineralization of copper and precious metals in part of the northern Antarctic Peninsula by Chilean and U.S. investigators [Vieira *et al.*, 1982; Alfaro and Collao, 1983; Pride *et al.*, 1981, this volume], and the mineral potential of the deeper horizons of the Dufek Intrusion by U.S. and USSR scientists, and others, as outlined in this volume.

The Antarctic Peninsula lies at a much lower latitude than the rest of Antarctica. The northern tip is also much closer to populated areas, being only 1300 km from Punta Arenas, Chile, and Ushuaia, Argentina. The climate is milder than that of coastal Antarctica with summer temperatures rising to 10°C on occasion. Much of the ice-free area of the Antarctic Peninsula is in rugged cliff-bound islands. Fast sea ice is largely absent in the northern peninsula area in the summer. However, icebergs are common and generally fast moving because of the high velocity of ocean currents. Rain falls occasionally during the summer, but even then most major storms are accompanied by driving snow. Winters are severe in both temperature and wind, and solid sea ice completely blocks the sea to marine transport in some areas. Any year-round exploration or mining activities would require the artificial environment of large buildings or underground installation; however, there are very few suitable unoccupied coastal sites remaining available for bases of operation. There are a number of permanent year-round national research stations on the northern Antarctic Peninsula and nearby islands, but about half of these are restricted to the western end of King George Island. When the United States decided to establish a permanent station in the Antarctic Peninsula in the 1960s, an aerial search was made of the entire west coast of the peninsula. Only one unoccupied site was found that allowed access by large supply ships, access to a snow runway on the adjacent icecap, a meager freshwater supply, and sufficient ice-free terrain on which to build a station adequate for about 10 winter-over personnel. This was on the south end of Anvers Island where the United States built and maintains Palmer Station. The sinking of the Argentine supply ship *Bahia Paraíso* in January 1989 at Palmer Station indicates how dangerous the approaches to this locality can be. The east side of the Antarctic Peninsula, south of James Ross Island, is essentially inaccessible to any type of ship during most years because of permanent sea ice. The U.S. icebreaker *Westwind* attempted

penetration of this area in the austral summer of 1983–1984, but was stopped by sea ice at the Antarctic Circle. On the return northward it was caught in moving sea ice that pressed it against the Larsen Ice Shelf, causing severe damage along half of the port side of the ship.

In conclusion, a major problem in Antarctic exploration and mining operations is the physical transport of people, fuel, food, supplies, and equipment to the Antarctic, and of waste and mining products out of the Antarctic. Transportation inland to a site of operations multiplies these problems by at least an order of magnitude. In any mining operation the removal of the desired product must be faced as a major cost. Efforts must constantly be maintained to reduce the volume and weight of everything transported within the interior of Antarctica. Construction materials and equipment will be the greatest transportation problem early in any operation, but in the long term, fuel will be the greatest mass. Currently, most fuel used in the Antarctic is Arctic diesel oil (Diesel Fuel—Arctic (DFA)).

Solar energy is available in abundance at most locations during the summer. Areas in the open, without surrounding mountains, except for cloudy days, will receive intense sunlight throughout each 24-hour period. As an example of such developments, drilling of the Quelccaya Ice Cap in 1983, at about 5500-m elevation in Peru, was carried out entirely with solar energy (L. Thompson, personal communication, 1989). Other aspects of polar drilling, both present and future, were covered by the First Polar Drilling Workshop at Ohio State University in November 1988. The proceedings will be valuable to any group planning or considering mining operations in Antarctica [Barrett, 1988]. Innovative developments may help to reduce transportation costs or allow cold season resupply and cargo export. An example is the suggested utilization of large submarines. Use of submarines for carrying valuable cargo under difficult conditions has been a reality since 1916, when German cargo submarines carried rubber, dyes, and strategic metals through a British blockade [McLaren, 1983]. Submarines towing large bladders for crude oil have been suggested for removing oil from Arctic submarine oil fields. These could certainly be considered as a means for allowing year-round production from potential Antarctic Continental Shelf oil production.

The experiences of expeditions and research programs in the Antarctic and of mining and petroleum developments in the Arctic are the basis from which planning will be based for future exploration, mining, and petroleum production in Antarctica. This paper has presented an extended description of some aspects of current logistic operations, especially in the U.S. Antarctic Program. These logistic operations have been extrapolated to suggest directions that might be taken in the future. However, the only real truism in Antarctic

operations is that it is impossible to plan for every contingency and condition. Flexibility and imagination will be among the most important tools for successful Antarctic enterprises.

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ENVIRONMENTAL IMPACTS OF EXPLOITING MINERAL RESOURCES AND EFFECTS OF TOURISM IN ANTARCTICA

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Whereas exploitation of nonrenewable resources of Antarctica awaits future exploration, discovery, and implementation of new technology, these developments are sufficiently near that a review of the environmental consequences is both justified and urgently needed. In evaluating the consequences of exploitation, the impact should be assessed with respect to probability of occurrence, magnitude and type of impact, duration of impact, and the probability of being able to recognize that impact has occurred. There can be little doubt that severe local impacts would result from resource extraction. The complete loss of land forms, soil types, and terrestrial biota seems an unlikely event in any Antarctic habitat because of the regional distribution of these features. However, the cold desert lakes may be unique and need special protection. The circum-Antarctic distribution of birds and marine mammals makes the complete loss of any one species unlikely as a result of resource development at any one place along the coast. The Specially Protected Areas concept should assure survival of species even if development were extensive. Similarly, impacts on marine environment, on the basis of present knowledge, would not likely eliminate any species. Repeated hydrocarbon spills could be very serious but would not likely prevent recovery. On the basis of present knowledge, there appears to be no compelling scientific reason for the banning of resource exploration provided sufficient Specially Protected Areas are established and exploration, development, production, and exploitation are conducted with all necessary precautions to minimize or prevent environmental impacts. A careful and complete risk assessment for each mining operation projected and a meaningful program of risk management must be required. Presently, insufficient information on biologically important interactions is available to enable management and policy decisions to be made. This is of considerably less importance away from the coast (deep inland), where biological activity appears to be nonexistent. Nevertheless, unperturbed Antarctic ecosystems are poorly understood, and how environmental impacts may affect the systems is largely unknown. It is possible that qualitative differences, not yet recognized, render the Antarctic ecosystems more susceptible to permanent damage than ecosystems elsewhere. Recovery from environmental insult under Antarctic conditions will be extremely slow. It may not occur in our lifetime. It is for these reasons that we must operate in the Antarctic with care and with an understanding and appreciation of the damage that we can render to that environment.

INTRODUCTION

The exploitation of nonrenewable resources of Antarctica lies in the future; nevertheless, it is appropriate to consider the potential environmental consequences of such exploitation while time still permits the acquisition of data necessary for better evaluation of those impacts.

Other papers in this volume have dealt with the known, potential, or speculative resources of Antarctica and have provided the necessary information for evaluating the possibility or probability of exploitation in the future. Our objective here is to provide the reader with background information for a better perspective on the physical and biological environment of the continent

and for an understanding of potential impacts consequent on exploitation.

To this end, the physical and biological environments are described, and some of their special or unique aspects addressed. Because the magnitude of potential impacts varies greatly, we believe a more useful service is performed by emphasizing impacts that would appear to be of major importance. Also, since Antarctica is neither a static nor a closed system, we recognize the importance of potential interactions that would change the status or magnitude of impacts on ecosystems. With respect to the biological characteristics, we have approached the assessment of potential major impacts on ecosystems by applying ecological principles, which,

while occurring throughout the biosphere, may be of different quantitative importance in Antarctica.

We will not catalogue the range of impacts that may occur, for this would lead to a repetition of published material [e.g., *Marlins*, 1977a, b; *Parker*, 1978a]. Rather, the scale of impacts in relation to the continent as a whole will be emphasized, and potentially critical interactions and their importance will be pointed out. In this context we define an "impact" as a change, reversible or irreversible, brought about directly or indirectly by human activity, and we define the "integrity" of the environment as the condition of a recognizable physical or biological state such that it retains all of its essential qualitative characteristics on a continent-wide scale. In the case of the biological state the key is its capacity to resist change due to impact (i.e., resilience) or to recover from impact (i.e., stability). For the physical environment, because of the time scale involved for its development and the possibility that it is the product of conditions that no longer prevail, recovery from impact to its present condition may never be achieved. However, because features are distributed on a regional scale, impact at one site will not eliminate any feature from the total Antarctic environment and thus from the sum total of the Earth's characteristics; on man's time scale, exploitation is likely to lead to permanent local change.

We shall not discuss here the subjective aesthetic qualities of the Antarctic continent. Rather, we shall examine those aspects that are amenable to scientific treatment, recognizing that serious gaps exist in our knowledge of Antarctica, which will limit the depth of our scientific treatment.

Important recent publications on resource development in Antarctica are *A Framework for Assessing Environmental Impacts of Possible Antarctic Mineral Development* [Elliot, 1977], *Environmental Impact Assessment of Mineral Resource Exploration and Exploitation in Antarctica* [Zumberge, 1979], and *The Environmental Implications of Possible Mineral Exploration or Exploitation in Antarctica* [Holdgate and Tinker, 1979]. Publications especially addressing biological areas of impact include *Conservation Problems in Antarctica* [Parker, 1972] and *Environmental Impact in Antarctica* [Parker, 1978a].

THE PHYSICAL ENVIRONMENT

Antarctica is geographically isolated from all other southern hemisphere landmasses. South America is 700 km from the South Shetland Islands which lie off the Antarctic Peninsula, and New Zealand, the next closest landmass, is about 2300 km distant. This geographical isolation is magnified by the seasonal pack ice belt that may spread as much as 1500 km northward from Antarctica. The physical isolation of Antarctica is further

compounded by the harshness of the climate, the continent being the highest, coldest, windiest, driest, and most lifeless on Earth [Joyner, 1985]. Neither trees nor deep-rooted plants exist on the continent.

Antarctica has an area of 14 million km², about 1½ times the size of the continental United States. Continental shelves increase the area by 4 million km². About 98% of the continent is permanently covered by snow and ice; ice-free areas are found principally on the Antarctic Peninsula, along a broad peripheral zone of the continent, and in the Transantarctic Mountains and the Ellsworth Mountains. Over most of the continent, ice forms broad domes that reach elevations greater than 4000 m and may cover entire mountain ranges such as the Gamburtsev Subglacial Mountains in East Antarctica. Summit elevations in the Transantarctic Mountains exceed 4000 m, and the highest point (Vinson Massif) on the continent (4897 m) is situated in the Ellsworth Mountains. Elsewhere in West Antarctica and the Antarctic Peninsula summit elevations are lower, and north of about 69°S on the Antarctic Peninsula the topography is particularly rugged.

The area free of ice and snow for at least part of the year, about 250,000 km², is mountainous, and it is only locally in coastal regions that areas of low relief and gentle slopes occur. Coastal plains are nonexistent. Large expanses of snow- and ice-free ground called "oases" or "dry valleys" are scattered around the continent. The two largest of these occur in southern Victoria Land: one comprises the Taylor, Wright, and Victoria valleys, which cover 2500 km², and the other, near the Koettlitz Glacier, covers 1200 km². Ice-free areas of 100–400 km², apart from those in the Transantarctic Mountains, are sparingly distributed around the continent; smaller ice-free areas are more common particularly in the north Antarctic Peninsula. In general, exposed rock and rock debris seldom cover more than a few square kilometers at any one place.

Within the ice-free areas, bedrock or unconsolidated transported materials, such as talus, moraines or till, beach deposits, and, locally, stream deposits, comprise the substrate for primitive soils and a variety of poorly developed patterned ground features [Everett, 1977; Tedrow, 1977; Walton, 1980]. In contrast to many Arctic soils, especially those of the tundra south of about 70°N latitude, Antarctic soils lack a significant vegetational cover and have only trace amounts of organic materials. In southern Victoria Land and to a lesser degree within the coastal oases, physical weathering dominates chemical weathering. The soils commonly lack horizons and, where best developed, display only a thin oxidized surface horizon overlying chemically unaltered materials. Locally, near-surface horizons may be found indurated with salts. Authigenic clays may form in some soils, but they are clearly subordinate to those derived residually by weathering. Because of the slow rate of

chemical and biological weathering, only a small ionic exchange complex (clays and organic matter) occurs and the soils have few available nutrients. In Enderby Land and other coastal "oases," warmer temperatures and more moisture produce soils with greater profile differentiation which is shown primarily by evidence of stronger oxidation and some eluviation of silts and clays. Northern hemisphere counterparts of these primitive soils are designated polar desert soils, most of which belong to the soil taxonomic order of Entisols that are found extensively at latitudes north of 70°N.

Ice-free areas on the western flank of the Antarctic Peninsula and adjacent islands have soils which generally show more strongly differentiated profiles. Because of the more moderate climate and higher annual precipitation, including rainfall, leaching is significant on well-drained sites and organic matter is more plentiful especially in areas associated with meltwater from snowbanks and near rookeries. The presence of large numbers of birds, and in some cases sea mammals, influences the availability of nutrient ions, especially nitrogen and phosphorus, and consequently aids the occurrence of certain vegetation.

Patterned ground, so characteristic of tundra and even polar desert areas in the northern hemisphere, is generally poorly expressed in Antarctica. The extreme dryness of much of the continent serves to inhibit the development of ice-rich permafrost, i.e., permanently frozen materials (rock or soil) in which ice occurs in quantities exceeding the available pore space. Dry permafrost, in which ice is absent or insufficient to fill the pore volume, predominates. Thus mechanical forces necessary for the production of most patterned ground are weak or absent. Nevertheless, in parts of the Antarctic Peninsula and offshore islands from about Anvers Island north and east to include the South Shetland Islands and the South Orkney Islands, ice-rich permafrost may be present locally, and periglacial landforms, more common.

During the spring and summer thaw, surface streams flow and groundwater movement is widespread. The volume of water is limited to melting of the local snow cover except where an ice margin abuts bare ground, and then there may be significant flow for several months particularly in the northern Antarctic Peninsula. Away from coastal areas, summer melting and surface accumulation of water are restricted to low elevations adjacent to large rock outcrops such as at or near the mouths of large glaciers debouching into the Ross Ice Shelf and to the ice-free valleys of southern Victoria Land and other oases. Parts of the ice-free valleys may have running water for limited periods in the summer, and some contain unusual stratified saline lakes [Angino, 1962; Angino and Armitage, 1963; Angino *et al.*, 1964, 1965] resulting from the internal drainage and accumulation of salts over long periods of time. Lake

Vanda in Wright Valley, southern Victoria Land, for instance, where the mean annual temperature is -18°C , is frozen at the surface but has saline water at $+25^{\circ}\text{C}$ at the bottom (70-m depth) [Angino *et al.*, 1965]. Saline lakes also occur in the Vestfold Hills [Kerry *et al.*, 1977].

The Antarctic ice sheet [Bentley *et al.*, 1964; Gow, 1965] forms a giant carapace over the continent and contributes to the unusually high average surface elevation of approximately 2500 m. Ice thickness in East Antarctica is generally >3000 m and locally >4000 m. Ice thickness in West Antarctica is generally <3000 m, but locally the base of the ice sheet may be >2000 m below sea level and the ice >4000 m thick. If the ice were removed, after isostatic readjustment (i.e., recovery from being depressed by the load of ice), East Antarctica generally would be a lowland, bordered by highlands, including subglacial mountain ranges (e.g., the Gamburtsev Subglacial Mountains that have been identified by seismic and radio echo sounding). Subglacial mountains may be more extensive than presently known. In contrast, West Antarctica would be an archipelago of several large islands separated by depressions and channels, some >1000 m deep [Bentley, 1972].

The ice sheet moves as a result of internal deformation, the upper part moving faster than the lower [Whillans, 1977]. Where the pressure-temperature conditions are suitable, water occurs at the base (wet-based ice), resulting in bottom sliding over the substrate. There appear to be two modes of flow, a slow mode with velocities of <100 m per year and a fast mode with ice streams flowing at >100 m per year, such as the ice streams draining from West Antarctica into the Ross Ice Shelf. The ice sheet moves outward to the edge of the continent where it terminates on land, in the sea, or in ice shelves.

Extensive floating ice shelves [Switchenbank and Zumbeke, 1965] characterize much of the Antarctic coastline. The formation and disintegration of ice shelves has been reviewed by Robin [1979] and Thomas [1979]. The largest, the Ross Ice Shelf, covers $550,000\text{ km}^2$; the Filchner Ice Shelf and the Ronne Ice Shelf together cover a comparable area, and other smaller shelves (e.g., Larsen Ice Shelf and Amery Ice Shelf) occur around the continent. The seaward margins of ice shelves advance and break off to form the tabular icebergs that are so distinctive of the Southern Ocean. These bergs, which commonly stand 30 m above the sea and sit approximately 250 m below the surface, often are several kilometers in length and occasionally attain huge dimensions (e.g., $160 \times 72\text{ km}$). The largest production of icebergs is in the Weddell Sea embayment. Ice shelves and the floating ice tongues of some of the larger glaciers also produce tabular icebergs by calving, and these ice tongues together with smaller glaciers or fringing ice margins produce smaller and less regular ice

masses that range in size down to the bergy bits that are ≤ 10 m across.

Icebergs occupy only a small portion of the sea that is covered by ice, the larger proportion being sea ice. Sea ice builds up each year from a minimum cover of approximately 2.6 million km^2 in March to a maximum of approximately 20 million km^2 in August-September. Estimates of sea ice cover vary widely, in part owing to interannual variations [Gordon, 1977; Zwally *et al.*, 1979a, b]. At the maximum the northern edge of the pack ice is at about 60°S , but in the South Atlantic sector it reaches 55°S . The sea ice consists of individual floes from 10 to 100 m across and up to 3 m thick; multiyear ice is much thicker, but its occurrence is largely restricted to the Amundsen Sea and the Bellingshausen Sea and the western Weddell Sea. The Weddell Sea area, with the greatest production of icebergs, also contributes substantially to the total sea ice cover around Antarctica. Better information is available for this sector than for any other area of the continent on the character and movement of sea ice [Ackley, 1979] and the impact of the prevailing winds on its movement [Schwerdtfeger, 1979]. Sea ice is driven and broken up by the wind, and in winter new sea ice forms in the open water between the floes. The northward drift of the sea ice leaves open water along coastal regions during early summer, while a belt of pack ice several hundred kilometers wide remains at lower latitudes. Whereas sea ice is wind driven, the tabular icebergs respond more to ocean currents because of their bulk below sea level. Thus icebergs and ice floes may not move in the same direction. Icebergs drift into lower latitudes than the sea ice and can occur north of the Antarctic Convergence. In a number of areas around the continent, the sea lacks any ice for much, and in some years for all, of the year [Gordon, 1977]. These areas, known as polynyas, are important for access to coastal regions.

Antarctica, in contrast to the Arctic, which is an ice-covered ocean surrounded by land, is an elevated ice-covered continent surrounded by a seasonally ice-covered ocean. The Antarctic climate is more severe than that of the Arctic [Lamb, 1965]. Summer mean temperatures range from 0°C in coastal regions to -35°C on the polar plateau of East Antarctica, whereas winter temperatures range from between -15° and -30°C on the coasts to -70°C on the polar plateau. The lowest temperature recorded on Earth is -89.2°C at Vostok Station (elevation 3488 m), and the lowest temperature on the coast is -60°C with winter means of approximately -10°C . A striking climatic gradient occurs across the Antarctic Peninsula, and on the Larsen Ice Shelf temperatures are about 7°C colder [Martin and Peel, 1978].

Temperature inversions, when the atmosphere is colder at the surface by as much as 30°C than at 1000 m, are common and are a major feature of the Antarctic

atmosphere [Schwerdtfeger, 1977; Weyant, 1967]. These inversions are caused by sustained radiative cooling. Inversions may occur at any time of the year and at any place but are particularly common in the winter months, when the atmosphere over the continent is most stable. Inversions are favored by calm or light wind conditions and decrease in strength or break down with increasing wind velocity, particularly when >15.6 m s^{-1} (30 knots).

Generally, the polar plateau is relatively cloud free with persistent winds of medium intensity. In contrast, the coastal regions have more variable conditions, the most striking of which is the katabatic wind; the cold dense air at the surface of the ice sheet flows downslope and may be funneled topographically through outlet valleys in the coastal mountains. In coastal regions where the ice sheet elevation decreases rapidly seaward, these winds may reach hurricane force or more than 35 m s^{-1} (70 knots) for many hours. The intensity of these downslope winds seems to be increased by the pressure gradients on the rearside of passing cyclones; however, low-pressure centers are not prerequisites, and the winds may be violent at any time. The speed of the katabatic winds drops dramatically away from the coast, and ships may stand offshore in light winds, while coastal stations are obscured by blizzards. Calm conditions in coastal regions or just inland do occur, but seldom for more than a brief time; nevertheless, in suitably located places such as ice-free valleys of southern Victoria Land, calms may persist for several days at a time.

More characteristic of coastal regions are easterly winds and the passage of storms generated by low-pressure systems that are themselves the result of the marked temperature gradient between the Antarctic continent and the subtropical high-pressure belt centered about 30° – 35°S . The depressions are generated most frequently in the mid-latitudes, and at any one time up to six low-pressure systems in various stages of growth and decay may be present around the continent. Individual depressions may form in less than a day, and at fullest extent they may be 2500 km or more across. The cyclonic centers move up to 2000 km per day and may follow one another with much greater frequency than in northern latitudes; there is little assurance of calm conditions between successive centers. High-pressure ridges blocking the predominant westerly migration of cyclones are comparatively rare and short lived. The southern parts of the cyclonic systems may penetrate coastal regions and bring strong winds and heavy snowfall. Annual snow accumulation is strongly related to incursions of warm, wet air masses in coastal regions.

The Antarctic Peninsula acts as a barrier to Southern Ocean storms, and this leads to the high precipitation on its western coast and correspondingly lower amounts on

the eastern or Larsen Ice Shelf side. Precipitation elsewhere around the continent decreases away from the coasts, and on the polar plateau it is so low that the plateau is classified as a desert (less than 5 cm of water equivalent per year). On the northern flank of the cyclones, strong westerly winds prevail. With the unimpeded progress of the centers due to the lack of land barriers in the Southern Ocean, the seas are among the stormiest on Earth. The belt of westerlies extends to about 45°S where the circumpolar circulation interacts with subtropical high-pressure systems, and thus the atmosphere over Antarctica and the Southern Ocean is coupled to that of the rest of the planet; a similar coupling occurs in the oceans.

The contrast in air masses just noted has an oceanic counterpart in the Antarctic Convergence, situated between 50° and 60°S, where colder Antarctic surface waters meet warmer water masses of the southern Atlantic, Indian, and Pacific oceans. Southern Ocean circulation has both zonal and meridional components [Gordon, 1970, 1977; Gordon and Goldberg, 1970]. The principal zonal flow, the Antarctic Circumpolar Current (ACC), moves eastward with surface velocities of 0.25–0.5 m s⁻¹. The strong westerly winds driving the surface current induce a northeastward drift of the surface waters, and thus a divergence is generated near the coast (the Antarctic Divergence) and a convergence (the Antarctic Convergence) where the cool Antarctic surface waters sink beneath warmer temperate latitude waters. The Antarctic Convergence shows a northward shift east of the Scotia Sea and a southward shift in the Macquarie Ridge-Campbell Plateau region. Superimposed on this simple circumpolar circulation are a number of cyclonic gyres, that in the Weddell Sea being the most important. The gyres tend to recirculate water so that in the Weddell Sea the water is colder and less saline than elsewhere around the continent, and sea ice tends to include more multiyear ice.

Circumpolar deep waters, which extend to near the ocean floor, have a southerly component of flow and thus bring warm saline waters from other oceans into the polar regions. These warm waters come to the surface at the Antarctic Divergence where they are cooled by heat loss to the cold atmosphere and diluted by the influx of fresh water in the form of icebergs and the excess of precipitation over evaporation. The cooled and diluted surface waters move eastward and northward toward the Antarctic Convergence where they sink below the Subantarctic waters and spread northward into equatorial regions.

South of the Antarctic Divergence, very cold saline waters are formed on the continental shelves; the generation of these cold saline waters is not entirely clear but appears to be related to sea ice formation and freezing of seawater onto the base of ice shelves. The salts are retained in the water which sinks and flows

across the continental shelves and down the continental slopes where mixing with warmer waters occurs. Antarctic Bottom Waters, so produced, flow northward throughout the world's oceans and return mixed with intermediate depth waters, the full cycle taking approximately 1000 years.

The upwelling waters at the Antarctic Divergence are not only relatively warm and saline, but also nutrient rich. This upwelling is the direct cause of the unusually high levels of biological productivity in the Southern Ocean.

THE BIOLOGICAL ENVIRONMENT

The biotic communities comprising microorganisms, plants, and animals with their associated environments represent the ecosystems (i.e., the community and its environment) of Antarctica. The ecosystems or parts thereof discussed here will be (1) the ocean, (2) ocean-dependent seals and birds, (3) the terrestrial (rocks, gravels, soils, snow, and ice), and (4) the freshwater lakes and streams, excluding information already detailed in the preceding section on the physical environment.

Ocean Ecosystems

Antarctic marine ecosystems possess greater biomass densities and perhaps 4 times the productivity per unit area than that of any other part of the oceans [El-Sayed and Mandelli, 1965; El-Sayed, 1967, 1970; McWhinnie, 1978]. Besides the greater primary production by the phytoplankton (i.e., especially diatoms), the standing crop of zooplankton exceeds that of other oceans, especially so in the Scotia Sea and the Antarctic Peninsula area where krill and copepods are most abundant. Although plankton biomass and presumed annual production rates are high, lack of information on the biomass beneath the ice cover and the patchy horizontal and vertical distributions complicate accurate quantification [Hopkins, 1971; Voronina and Zadorina, 1971; Voronina, 1972; McWhinnie, 1978]. Greater details of the biomass, distribution, and species composition of the marine phytoplankton and zooplankton are given by Heywood and Whitaker [1984] and Everson [1984], respectively.

A rich benthic fauna occurs on the shelf of Antarctica, generally from approximately 30 m, above which the ice scour is common, down to approximately 500 m, where faunal densities decline [Parin and Filatova, 1972]. However, the flora and fauna occur at still shallower depths and exhibit greater diversity on the Antarctic Peninsula and Subantarctic islands [White, 1984].

Data on the abundance of fish and squid (nekton) are incomplete. However, the stomach contents of whales, seals, and penguins suggest that squid are important in the pelagic food chain. Sperm whales consume large

quantities of deepwater squid [Klumov and Iukhov, 1975; Laws, 1977]. Indeed, there is good reason to expect, despite lack of data, that the fish and squid biomass probably also reflects the proven higher phytoplankton and zooplankton productivities of Antarctic circumpolar waters.

An important difference between the Antarctic ocean ecosystem and the ecosystems of marine environments elsewhere is the dominance of krill (euphausiids) instead of a diverse community of planktonic organisms [McWhinnie, 1978]. Krill are the major link between the primary producers and higher trophic levels in the Antarctic ocean [Everson, 1984]. They are the primary food source for the much reduced current population of baleen whales (excluding the sei), some 15–30 million crabeater seals, >50 million penguins and countless flying birds [Mackintosh, 1970; Laws, 1977]. Furthermore, different penguin species apparently select different age groups of krill [White and Conroy, 1975]. Fish and squid also eat krill, which in turn links them to the relatively few branches of the rather simple Antarctic marine food chain. Yet another unusual feature of krill is that they are one of the few marine plankton groups with the ability to synthesize vitamin A [McWhinnie, 1978].

Ecosystems of Seals and Birds

The ocean-dependent seals and birds, found in numerous locations near the coast of the Antarctic continent, Antarctic Peninsula, and islands, both on shore and in the pack ice, intimately link the land and marine environment. The coastal areas are sites for breeding, moulting, resting, and recovery for seals and birds which derive their food, directly or indirectly, from the sea.

Of the >30 million Antarctic seals, the crabeater, Weddell, leopard, and Ross seals are found in the pack ice or on shorelines at essentially all latitudes around the continent. Reasonable estimates of the numbers and feeding habits of these seals exist, but little is known of their breeding except for the Weddell seal [Oritsland, 1977].

Crabeater seals comprise about 95% of the total seal numbers. This species occasionally comes onto land but more commonly is found in relatively unconsolidated pack ice, apparently feeding almost exclusively on krill. Crabeaters breed and pup during the austral spring [Erikson and Hofman, 1974; Oritsland, 1977].

The Weddell seal occurs along perennial tide cracks in annual or multiyear ice. Comprising no more than 2% of the Antarctic seal numbers, they feed on fish, crustaceans, arthropods, cephalopods, and euphausiids (i.e., krill) [Dearborn, 1965].

The leopard seal may be found on land and in pack ice near penguin colonies. While taking some penguins for

food, leopard seals also eat krill, fish, and other seals [Penney and Lowry, 1967; Hofman et al., 1977].

The Ross seal constitutes perhaps 1% of the Antarctic seal biomass and inhabits rather consolidated pack ice. Cephalopods along with some fish and krill comprise the food for this species [Erikson et al., 1971; Oritsland, 1970].

Though not exclusively Antarctic in distribution, the southern elephant seal and, to a lesser extent, the southern fur seal occur locally in considerable numbers south of 60°S, where they are seen as herds along shores on the northern Antarctic Peninsula and Subantarctic islands. Fur seals feed upon krill, fish, and cephalopods, and the southern elephant seal eats chiefly cephalopods and fish. These two species suffered from overexploitation by nineteenth century sealers but have recovered rapidly [Laws, 1977].

A number of the fauna and flora of Antarctica may be found in Specially Protected Areas, for example, Litchfield Island on the Antarctic Peninsula. The larger animals, of course, leave such areas to feed in the ocean, but many return for breeding, moulting, etc. [Parker, 1972].

Of great importance is the heavy fur that these seals have for insulation, for it is well established that oil spills can cause fur to lose its insulating qualities, rendering such species particularly susceptible to thermal stress [Siniff, 1977; Marlins, 1977a, b]. As with the southern fur seal, the southern elephant seal also congregates in herds, and hence more land is required for their activities than the four previously discussed truly Antarctic seal species. Laws [1984] presents additional data on the seals, their food, reproduction, and distribution in Antarctica.

Nineteen species of birds breed south of 60°S, several in vast numbers or densities [Risebrough, 1977]. As with the seals, the food of Antarctic birds is intimately linked to the ocean. All bird species breed on land except the emperor penguin, which breeds mainly on ice shelves [Budd, 1961; Laws, 1977]. No two Antarctic bird species have identical food requirements or breeding habits, which is thought to maximize the species diversity and total bird numbers in Antarctica [Risebrough, 1977].

Prévost [1976] has estimated the current numbers and total biomass of birds inhabiting Antarctica and concluded that the Adélie penguin comprises, by far, the greatest biomass. It feeds primarily on krill. The significant decline of the overexploited baleen whales since the turn of the century has led to the suggestion that the surplus krill might effect population increases in other krill-dependent fauna [Mackintosh, 1970; Gulland, 1970; Laws, 1977]. Available evidence, however, does not support this idea, except for a small increase in the chinstrap penguin [Sladen et al., 1964]. However, many marine populations (e.g., fish, squid) have not been

surveyed [Mackintosh, 1970; Conroy, 1975; White and Conroy, 1975; Prévost, 1976].

Ice-free space for breeding, which is severely limited in Antarctica, has been suggested as the major "brake" upon expansion of the bird population, such as the Adélie penguin [Gulland, 1970]. However, no evidence for space limitation has yet been shown [Stonehouse, 1970], and available food in winter appears to be the chief factor limiting population size; the latter factor applies when areas of open water are few and far from the continental shores [Prévost, 1976].

The Adélie penguin, which numbers 27–50 million individuals or 122,000–225,000 metric tons biomass, feeds almost exclusively on krill within the pack ice zone, as does the less abundant chinstrap penguin. The gentoo penguin feeds on both krill and fish. Colonies occur where sea ice opens early in spring and where ice tends to disperse in summer [Stonehouse, 1967, 1975; Laws, 1977]. In addition to predation by leopard seals, the eggs and young of these penguins are often preyed upon by the south polar and brown skuas. Skuas also eat krill and scavenge station dumps and many other food sources. Generally, skuas breed near or within penguin rookeries [Risebrough, 1977].

The emperor penguin, numbering about 570,000 individuals, breeds on ice shelves except for two localities where the species breeds on shingle beaches [Budd, 1961; Laws, 1977]. About 30 known emperor penguin colonies exist in Antarctica. Unlike most other Antarctic birds which breed in the austral spring, emperors incubate their eggs during the winter. Colonies range from 200–50,000 or more pairs. Emperor penguins feed on fish and squid mainly [Stonehouse, 1975].

Other Antarctic birds include the macaroni penguin, giant fulmar, cape pigeon, southern fulmar, Antarctic petrel, Antarctic prion, Wilson's storm petrel, snow petrel, black-bellied storm petrel, sheathbill, blue-eyed shag, southern black-backed gull, and Antarctic tern [Prévost, 1976]. Their feeding and breeding habits have been reviewed by Laws [1977] and elaborated still further by Croxall [1984].

Terrestrial Ecosystems

In striking contrast to the high productivity, large biomass, and great expanse of the Southern Ocean south of the convergence, Antarctic terrestrial environments are the most inhospitable for life on Earth and are confined to less than 2% of the continental landmass. Terrestrial ecosystems are characterized by low species diversity, small biomass, slow turnover rates, and simplified food webs with few trophic levels or branches [Parker, 1978b]. The low rates of energy flow and nutrient cycling and slow community development impart to these ecosystems a greater sensitivity to perturbations from which they also recover more slowly. A

pronounced gradation in terrestrial Antarctic ecosystems occurs, ranging from those in the lower-latitude, moister, and warmer maritime zone of the Antarctic Peninsula to the higher-latitude, cooler, desertlike, ice-free valleys. These are intimately associated, not only with climate differences, but with various types of soils [Walton, 1984]. Terrestrial Antarctic ecosystems include communities of plants, invertebrates, and microorganisms (1) on rocks, (2) within rocks, (3) on and in soils, or (4) on adjacent snow or glaciers. Lakes and melt streams occurring within these ice-free areas will be discussed separately [Smith, 1984; Block, 1984].

The dominant flora within the terrestrial environment comprise primarily bacteria, algae, fungi, lichens, mosses, and liverworts (approximately 700 taxa total) [Rudolph, 1977]. The invertebrate animals consist of microarthropods (insects and mites), nematode worms, tardigrades, rotifers, and protozoans (approximately 150 taxa total) [Llano, 1962; Rudolph, 1977; Parker, 1978b]. The presence of seals and birds, the latter nesting in some cases considerable distances (>100 km) inland, exerts a considerable influence on the terrestrial microbiota, flora, and fauna, usually enhancing their productivity and increasing diversity and biomass.

In maritime Antarctica the west coast of the Antarctic Peninsula as far south as 68°, the inland archipelagoes of the South Shetland Islands, South Orkney Islands, South Sandwich Islands, and just fringing parts of East Antarctica, where environmental stresses are less severe, the biomass and diversity of terrestrial life are increased and may include a few flowering plants propagating vegetatively, numerous mosses and liverworts, and fleshy fungi [Rudolph, 1977; Parker, 1978b; Smith, 1984]. Lush green carpets and turves of moss and lichen-coated rocks and associated fauna are characteristic of those moister, maritime areas of Antarctica and are found, for instance, on Litchfield Island, a Specially Protected Area near the U.S. Palmer Station.

Probably the most thoroughly investigated terrestrial ecosystems in maritime Antarctica are those on Signy Island, South Orkney Islands [Davis, 1981]. The two major communities are those of the dry moss turf (DMT) and wet moss carpet (WMC). DMT is dominated by the mosses *Polytrichum alpestre* Hoppe and *Chorisodontium aciphyllum* (Hook f. et Wils.) both with lichens covering the bare rock. WMC is dominated by *Calliergon sarmmentosum* (Wahlb.) Kindb., *Calliergidium austro-stamineum* (C. Muell.) Bartr., and *Drepanocladus uncinatus* (Hedw.) Warnst with the liverwort *Cephaloziella varians* (Gottsche) Steph. Unlike Arctic tundra, temperate, and tropical terrestrial communities, vascular plants, annelids, molluscs, winged insects, and truly terrestrial vertebrates are lacking. However, associated with DMT and WMC are algae, bacteria, fungi, protozoa, rotifers, nematodes, tardigrades, springtails, and mites. In this moister, milder

maritime area associated with the Antarctic Peninsula where mean monthly temperature for 4–5 months is $>0^{\circ}\text{C}$, the terrestrial communities contain >100 species, excluding bacteria and fungi. Both DMT and WMC have primary producers (mosses, lichens, liverworts, algae), decomposers (bacteria, fungi), primary consumers (protozoa, rotifers), and secondary consumers (nematodes, tardigrades, mites). WMC is anaerobic below approximately 3 cm, in contrast to DMT, which consequently possesses the highest biomass, productivity, and respiration. WMC has the greatest accumulation of dead organic matter or peat.

Recent studies of succession on recent and old glacial till and moraines on South Georgia have provided additional evidence for the slow potential recovery rates for terrestrial communities [Smith, 1984]. Such rates are quite certain to be still slower at high altitudes which are colder and drier.

Elsewhere where sufficient moisture occurs and where collecting activities or atmospheric pollutants from stations, such as oxides of sulfur or nitrogen, have not been excessive, rocks may be luxuriantly colonized by mosses, slow-growing lichens, and a few algae. In the colder continental environments at high latitudes, plant life is often restricted to altitudes where orographic clouds or prevailing moist air can provide the essential moisture to those communities [Llano, 1962].

A second, even more unusual rock ecosystem is that of communities of algae, fungi, and bacteria, some of which seem to form a symbiotic association that occurs within fractures in semitransparent rocks, for example, orthoquartzite [Friedmann, 1978; Friedman, 1982]. This endolithic microenvironment is widespread in the ice-free valleys, where the rock space interior is moist in relation to the exolithic, desiccating valley air.

A third ecosystem is that of loose soils which, depending on moisture and nutrient status, texture, and stability, support a varying biota of fauna, bacteria, algae, fungi, protozoa, mosses, and other flora. Antarctic soils, like those elsewhere, result from the interaction of parent material, climate, topographic position, and time. Vegetation or faunal influences are fairly minor, except in maritime Antarctica and around penguin rookeries [Allen and Heal, 1970; Cameron et al., 1970; Everett, 1977; Ugolini, 1970, 1977]. Mechanical weathering, that is, frost shattering and salt weathering, thus produce a variety of gravelly and sandy soils usually retaining the color of the parent rocks and often low in moisture and cation exchange capacities, high in salinity and low in organic matter and some nutrients (PO_4) [Everett, 1977; Parker et al., 1982].

The cold desert soils that occur in nearly every continental ice-free valley (e.g., southern Victoria Land, the Forrester Range, etc.) often possess an insignificant microbial community with only sparse heterotrophic bacteria being demonstrably present. Claims of

entirely sterile soils or endemic microorganisms have also been made [Cameron et al., 1970; Cameron and Ford, 1974; Parker et al., 1977a, 1982]. In contrast, soil on the maritime Antarctic Peninsula exhibit leaching, which leads to a soil profile with visible horizons [Allen and Heal, 1970; Everett, 1977]. Here salts have been removed, and the desalinized, moist, more temperate soil usually supports mosses and other, more diverse vegetational and faunal components, leading to a significant organic matter accumulation. This largely undecayed moss peat occurs in the northern maritime Antarctic where it reaches depths of ≥ 2 m but possesses permafrost below approximately 25 cm. In and near penguin rookeries, ornithogenic soils develop which are organically and nitrogenously enriched and support an extensive growth of algae and microorganisms [Ugolini, 1970; Walton, 1984].

Melting firn snow comprises another terrestrial ecosystem in which communities of red, yellow, and green snow algae exist together with other microorganisms. These have been little studied, but apparently they occur throughout the maritime Antarctic, in Wilkes Land, and Enderby Land, and probably on any coastal snow or ice where water persists for part of the austral summer [Llano, 1962; Curl and Becker, 1970; Wharton et al., 1985].

Algae growing in cryoconite holes on top of glaciers in southern Victoria Land have been reported recently [Wharton et al., 1985] and are known to occur in the South Orkney Islands, Antarctica Peninsula. These are known elsewhere in the world, and their community composition reflects that of the surrounding soils and lakes.

It is interesting that, whereas the terrestrial communities in their environmental settings may be considered unusual or unique, the occurrence of endemic species within these communities is sparse. That is, the biota of terrestrial Antarctica, especially the microorganisms (algae, protozoa, bacteria, fungi), are generally ecophenes or adapted strains of cosmopolitan species [Hirano, 1965; Cameron et al., 1970; Parker et al., 1972; Seaburg et al., 1979].

Freshwater Ecosystems

Lakes, ponds, pools, and ephemeral glacial or snow bank melt streams comprise a wide variety of environments, ranging in size, amount of liquid water (versus solid ice), nutrient richness and productivity, and freshness. Large streams are absent from Antarctica; the Onyx River in Wright Valley, southern Victoria Land, is the longest (approximately 15 km). Throughout the coastal ice-free areas on the Antarctic Peninsula and associated islands ringing the continent, there are numerous pools and ponds and some small lakes. For the most part these are fresh and contain algae, bacteria,

fungi, protozoa, sometimes moss, and microfauna [Llano, 1962; Parker *et al.*, 1972; Heywood, 1984; Parker and Simmons, 1985]. Freshwater shrimp also occur throughout the maritime Antarctic and near Palmer Station, for instance, occur in a small lake rendered eutrophic by airborne ammonia derived from an upwind Adélie penguin rookery [Wodehouse and Parker, 1981]. Heywood [1972, 1977, 1984] and Priddle and Heywood [1980] have reviewed the range of lake types found throughout Antarctica, and Hirano [1965] and Seaburg *et al.* [1979] have discussed the distribution of algae, which largely reflects the simplicity of the primary producer communities occurring within these aquatic ecosystems, their diversity and foodweb networks diminishing generally with increasing latitude southward. Despite their more maritime aspect, such lakes of the Antarctic Peninsula still possess lower species diversity and constitute simpler aquatic ecosystems than typical Arctic lakes, such as those studied by Jordan *et al.* [1978] and Michael *et al.* [1978].

While melt streams from glaciers or snow banks are ephemeral, they often abound with life. The flow of nutrient-carrying water encourages luxuriant growth of algae and attached animals and other organisms not usually present in lakes and ponds.

Lakes, which are by far the most unusual and interesting ecosystems compared with lakes elsewhere in the world, occur in the cold ice-free valleys, so-called "desert oases." Numerous lakes, ponds, and short melt streams occur within the four major "oases" namely, the Schirmacher Hills (70°45'S latitude, 11°40'E longitude), the Vestfold Hills (68°35'S latitude, 78°15'E longitude), the Bunger Hills (77°00'S latitude, 162°52'E longitude), and Victoria Land (70°–80°S latitude, 160°–170°E longitude), the latter containing perhaps the most unusual (unique) lakes of all. This oasis or ice free area has been ice free for perhaps 4 million years, and at least some of the lakes therein may have originated 300,000 years ago [Hendy *et al.*, 1977, 1978], which seems surprising in that they have not undergone eutrophication as have most lakes elsewhere which are considerably younger. Rather, these lakes remain oligotrophic, at least in part owing to limiting phosphorus and light, even though they lack outflow and should accumulate nutrients [Hoehn *et al.*, 1977; Parker *et al.*, 1977b; Parker and Simmons, 1985]. In southern Victoria Land within a 10⁴ km² area there are lakes frozen solid (e.g., Lake Vida) and lakes with permanent ice cover but with water beneath. Among the latter are lakes with saline bottom water overlain with freshwater (e.g., Lake Bonney and Lake Vanda) [Angino and Armitage, 1963], lakes entirely fresh and isothermal (e.g., Lake Hoare and Lake Joyce), a lake with 25°C bottom water (i.e., Lake Vanda) [Angino *et al.*, 1965], and a pond saturated with a CaCl₂ brine (i.e., Don Juan Pond). In the

Vestfold Hills another variety, unfrozen hypersaline mixed lakes, occurs [Kerry *et al.*, 1977].

The biota in these lakes have low species diversity and biomass. Solid frozen lakes often have a blue-green algal mat community living at the ice-mud interface. Lakes with a water column beneath permanent ice possess both a plankton and an attached benthic algal mat community. The plankton communities consist of green and cryptophyte algae, as primary producers, heterotrophic bacteria and yeasts, but only rarely any well-developed fauna or food chain (i.e., protozoa, zooplankton). The benthic algal mats comprise blue-green algae and diatoms, as primary producers, bacteria and other heterotrophic microorganisms, with sparsely occurring protozoa, tardigrades, rotifers, and nematodes as consumers [Kerry *et al.*, 1977; Parker *et al.*, 1977b; Parker, 1978b; Seaburg *et al.*, 1979].

Specific, seemingly unique, features of these permanently ice-covered lakes in southern Victoria Land include the following: (1) lack of wind-generated turbulence; (2) algal species that are psychrophilic, that is, unable to grow above 20°C; (3) supersaturated oxygen and probably carbon dioxide deficiency in the water, which may induce excessive photorespiration [Tolbert, 1974] and excretion of extracellular organic substances, such as glycollate; (4) algal mats which entrap oxygen, tear loose, float upward beneath the ice, freeze into the ice, and through ablation loss, reach the upper ice surface in viable condition, dry up and blow away, and hence escape from the lakes; (5) algal mats which remain in the lakes, binding sediments and precipitating minerals (e.g., CaCO₃, calcite) and hence are living cold freshwater stromatolites; and (6) unique or especially unusual chemistry (e.g., CaCl₂, Don Juan Pond).

These and other features of the southern Victoria Land lakes, either separately or in combination, are unique and not known in lakes from other regions of Antarctica or the world [Parker and Simmons, 1985]. Also see Wilson [1965], Parker *et al.* [1977b], Seaburg *et al.* [1979], and Heywood [1984].

APPLICATION OF THE ECOSYSTEM CONCEPT TO ENVIRONMENTAL IMPACT IN ANTARCTICA

The ecosystem concept embodies a number of ecological principles which are relevant to an evaluation of the environmental impact. These principles are the major basis by which we have identified areas potentially vulnerable to impact from human activities in Antarctica. Such vulnerable areas, so-called "pressure points," within ecosystems already have been identified in terms of impacts caused by scientific and logistic support activities related to the United States' presence in Antarctica [Parker, 1978a; National Science Foundation, 1979]. The principles in general are discussed by Collier *et al.* [1973], Krebs [1978], Ricklefs [1973], and

Whittaker [1975], the latter being especially valuable. While ecologists seemingly treat ecosystems as natural definable and distinguishable entities within the biosphere, most ecosystems are mainly conceptual and are restricted to artificial definition of their boundaries. Nevertheless, ecosystems, by virtue of their component environments and interacting populations, offer convenient conceptual units with which to detect and judge changes that may have been induced anthropogenically. Ecosystems have identifiable structures and functions. They exhibit "... a kind of metabolism—complex patterns of transfer, transformation, use, and accumulation of inorganic and organic materials" [Whittaker, 1975].

A key property of an ecosystem is homeostasis, which concerns the natural maintenance of equilibrium in the system by control mechanisms and feedback. Homeostasis is the sum of all processes and natural mechanisms by which an ecosystem preserves its integrity. Homeostasis for an ecosystem involves two groups of mechanisms: biodemographic and biogeochemical [Collier *et al.*, 1973]. "Biodemographic regulation [concerns] control of numbers and biomasses of organisms belonging to various trophic groups and occurs through the operation of density-dependent factors on populations" "Biochemical regulation" . . . concerns . . . "the action of negative feedback controls which operate to reestablish the normal concentrations of chemical nutrients in available ecosystem pools following a disturbance." These two control mechanisms are generally biological in that the organisms respond behaviorally or physiologically to effect the regulatory steps [Collier *et al.*, 1973].

The homeostasis of an ecosystem thus determines its stability, or its ability to return to the original state after disturbance. At least to some extent, the homeostasis of an ecosystem also determines its resilience, or its ability to persist essentially unchanged during perturbations. An important point here is that ecosystems differ markedly with respect to their degrees of stability and resilience to one or more types of perturbation. Communities within ecosystems can be very resilient (resistant) and unstable (poorly recoverable), while others can be very stable and quite nonresilient. Furthermore, the idea so commonly voiced "... that diversity causes stability . . . or resilience . . . is not supported by field or laboratory data, and the attributes of individual species may be more significant than diversity in general . . ." [Whittaker, 1975]. As will be seen, lack of adequate scientific information on the homeostasis of Antarctic ecosystems has prevented any reasonable quantitative assessment of their stability or resilience with respect to impacts arising from resource exploration and exploitation. However, we suggest that the more sensitive ecosystems are those which are confined in their distribution in increasing order of importance,

such as bird or seal colonies, terrestrial plant and microbial communities, and unique lakes. By contrast, the vaster and more diversified marine ecosystem is more resistant to impact but nevertheless vulnerable to exploitation especially because the high seas are not protected under the Antarctic Treaty [Bonner, 1984].

Assessing the stability and resilience of an Antarctic ecosystem is difficult, if not impossible. Populations, communities, and ecosystems under short-term observation may seem stable; this leads to an exaggeration of their apparent stability or resilience. Other ecosystems show both regular and irregular cyclic fluctuations in component populations. Usually the irregular cycles are limited by time for favorable growth, and the regular ones are caused by other factors. Cyclic patterns, whether seasonal, annual, or longer term, do not affect the long-term stability of an ecosystem unless disturbed at a time when the temporary stability or resilience of the ecosystem has declined so as to be permanently damaged.

While cyclic patterns are nondirectional, communities and ecosystems may change directionally through succession. Succession is caused either by earlier species creating conditions which favor later ones or by earlier species inhibiting one another, thereby enabling species replacements [Krebs, 1978]. For Antarctica we have sometimes assumed, for lack of contradictory information, that the present state of ecosystems is natural and unchanging, that the ecosystems represent the optimum, that the maximum carrying capacity has been achieved, and that all the niches have been filled, assumptions that may be incorrect.

Species diversity evolves naturally, and new species are introduced or invade even as far as this seemingly remote continent. This principle is exemplified by the successful introductions of exotic species (rabbits, goats, cats) to the Subantarctic islands [Bonner, 1984] and possibly by recent failures to establish sterile soils in many locations of southern Victoria Land's dry valleys formerly claimed to be abiotic like Mars [Cameron *et al.*, 1970; Parker *et al.*, 1977a, 1982]. The principle that "... no two species will occupy the same niche, using the same resources at the same time and place and subject to the same limiting factor, in the same stable community" [Whittaker, 1975], nevertheless, should apply. However, if the resources for biota in Antarctica are not fully utilized, or if the rate of dispersal and colonization by new species has been slow and has not, as yet, achieved its upper asymptote, then succession of Antarctic ecosystems is incomplete.

This idea applies especially to terrestrial and freshwater ecosystems, less to those of the ocean. Furthermore, it is reasonable to anticipate that the processes of invasion and colonization, increase in species diversity, succession and a rapid approach to a climax community, competition and operation of the competitive ex-

clusion principle, all will be accelerated by increased human activities in Antarctica which would accompany resource exploration and exploitation. Therefore an important point is that when the community structure or function is observed to change, the cause of that change must be confirmed, for it may be due to a natural cyclic, successional, evolution-based phenomenon rather than human perturbation. Indeed, beyond inorganic nutrients and foods as substances involved in community metabolism, the allelochemicals (i.e., chemicals produced by one species which influence another species) are natural and may well influence the apparent integrity of an ecosystem or its component community structure and function [Whittaker, 1975].

What regulates population growth, and what determines average abundance? In general, three categories define the answers to these two questions: (1) density-dependent factors such as predators, parasites, and diseases; (2) climate; and (3) other density-dependent and density-independent factors. In specific terms, nutrient availability, water availability (on land), and temperature are important factors controlling productivity and hence the ultimate structural complexity of a community within an ecosystem. In Antarctica, phosphorus, nitrogen, trace elements, light, salinity, water, and oxygen all have been implicated as limiting productivity, and temperature, as limiting decomposition and recycling nutrients for certain ecosystems.

Simple, nondiversified or few-branching ecosystems, in practice, can be more sensitive to perturbations, that is, less stable and less resilient, because the interrelationships among organisms are reduced, often more binding or dependent, and less versatile. Counteracting this vulnerable feature are large biomasses, as with the krill with their widespread distribution, which should impart stability, if not also resilience, to a breeding population.

One often cited weakness of a simple ecosystem is its potential susceptibility to "bioconcentration" effects. Bioconcentration is responsible for accumulation of such substances as chlorinated hydrocarbons, polychlorinated biphenyls, lead, mercury, radio isotopes, etc., in progressively higher levels of food chains. Normally, the chief vector is water or the atmosphere. The end result of bioconcentration can be acute or chronic (slow-developing) effects upon population or individuals and can influence reproduction, longevity, stability or resilience, and more subtle physiological processes seemingly unrelated to the bioconcentrated substances. Without directly killing off a population, substances bioconcentrated can upset the delicate balance which some species have within their component ecosystems such that the population decline may appear perfectly natural. In this sense, that is, change in an ecosystem without identified cause, one of the most disturbing consequences of environmental impact is manifest.

In summary, properties of Antarctic ecosystems which we have tried especially to identify toward assessing potential major impact that might destroy their integrity are as follow: (1) degree of homeostasis, with respect to stability and resilience; (2) degree of succession, or whether natural cyclic patterns are known; (3) identification of key density-dependent or density-independent factors; (4) degree of complexity (or simplicity) and size of the ecosystem; and (5) vulnerability to bioconcentration.

Unfortunately, these ecological concepts are useful only in the context of adequate information, the lack of which for Antarctica constitutes the major weakness in our impact assessment. What little information is available on this subject has been reviewed from an historical and political perspective by Bonner [1984].

IMPACTS OF MINERAL RESOURCE DEVELOPMENT

Recent reports on Antarctic nonliving resources have emphasized oil and natural gas and considered metalliferous ores or nonmetallic minerals to be of minor importance. The emphasis probably stems from the unqualified reports of the probability of vast quantities of oil and natural gas being present on the Antarctic continental shelves coupled with the highly sophisticated development of offshore oilfield technology. Although a wide range of resources may indeed be present, no economically exploitable resource has been found to date (1990). Thus all studies of the impact on the environment of development are hypothetical. Nevertheless, if normal economic market constraints are assumed to prevail, it would appear that the excessive cost penalty of operations and mineral extraction in Antarctica can be overcome only by the scale of operation, by the occurrence of a high unit value commodity, on the assumption of rapidly escalating costs of raw materials, or on the increasing scarcity of a particular mineral commodity elsewhere in the world.

We have elected to consider oil and natural gas exploitation and a generic approach to any high unit value commodity. In this, our approach does not differ from earlier reports, but in our perspective of the environmental consequences we have chosen to evaluate impacts from the viewpoint of the continent as a whole.

Oil and Natural Gas

As others have noted [e.g., MacDonald *et al.*, 1988], the known geology suggests that oil and natural gas are unlikely to occur on land except in the northern Antarctic Peninsula. Spletstoeser [1982] has developed a possible means of exploiting hydrocarbons in this area by means of tunneling beneath the sea from a facility on land. The most likely areas for such resources are the

continental shelves under the Ross, Weddell, Amundsen, and Bellingshausen seas and on the shelves adjacent to the Antarctic Peninsula. On the Antarctic Peninsula, impacts on the terrestrial communities such as the dry moss turf or wet moss carpet [Davis, 1981] or upon lakes [Wodehouse and Parker, 1981] are very likely. The effects of petroleum hydrocarbons on the terrestrial or lake biota of Antarctica have not been studied, but one might expect that a marked change in phytoplankton, elimination of fauna, and other changes in community structure and functions would result similar to those reported for the Arctic [Jordan et al., 1978; Michael et al., 1978] and locally like the kills of krill and limpets resulting from spills similar to the spill of the *Paradise Bay* ship disaster at Palmer Station [Barinaga and Lindley, 1989].

In general, there are four stages in the development of a commercially productive field: regional geophysical surveys, an exploratory drilling program, the installation of production facilities, and continuing production of oil and gas. The first stage involves geophysical surveys, principally multichannel seismic surveys but possibly augmented by other techniques, such as are routinely conducted on land or in coastal areas worldwide. Initial reconnaissance surveys guide the exploration program to areas for detailed surveys which then identify the most promising areas and structures for the second phase, the exploratory drilling. The number of exploratory wells necessary to define a field is variable but can run into double figures, particularly since several "dry" holes are not uncommonly drilled before a productive zone or structure is located. Exploratory drilling on the continental shelf could be conducted from drilling ships, semisubmersible platforms, or drilling platforms resting on the seafloor. Depending on location, shore facilities in support of a continental shelf operation might also be constructed.

The third stage includes installation of production facilities such as drilling production wells, wellhead completion operations, construction of pipelines, collector lines, possibly brine disposal wells, and associated systems for storage and tanker loading. This period of major construction would require housing and other facilities for the construction crew, port facilities, and probably an airstrip. Although storage and loading facilities might be constructed out at sea on the seafloor, a land-based operation is more likely. The ensuing production stage would require a much smaller maintenance staff, but there would then be a regular schedule of tankers.

It is assumed that the best available operating and technological procedures would be employed and all precautions taken to avoid accidental contamination of the environment. This includes use of blowout preventors, burial of all structures under the seafloor at water depths where ice scour is possible, continuous monitor-

ing of the weather by surface and satellite observations in order to anticipate hazardous conditions and take precautionary measures, continuous sea ice and iceberg monitoring with the same objective, and development of equipment and methods to minimize accidental spills on drilling platforms, at tanker terminals, and at storage facilities. It is assumed that natural gas would be flared only when necessary and that it would normally be returned underground for pressure maintenance or, although unlikely, liquified and stored for transport as liquid natural gas.

The fourth and final stage, that of continuing production, is one that demands attention. It is during this phase that the probability of major environmental damage is, in our opinion, greatest. Human beings are sometimes careless, and while never intended, accidents can and do happen. A major spill, accident, etc., that would have minimal damage to the ecosystems or environment elsewhere could have a major impact on the large unknown biological balance existent in and around Antarctica.

Lastly, it is assumed that the handling and disposal of all waste products associated with production activities, including sewage, would be designed for minimum impact. Furthermore, it is also assumed that designated Specially Protected Areas and Sites of Special Scientific Interest would not be violated. And as far as possible, operation in the vicinity of such places would be sited to minimize any potential impact. Operational objectives and directions would be guided by the "Convention on the Regulation of Antarctic Mineral Resource Activities" [Antarctic Treaty, 1988a, b]. With such precautions or restrictions, impacts of exploration and installation of production facilities for oil or natural gas should be localized or temporary. Marine ecosystems should largely be unaffected, and only locally would terrestrial ecosystems receive permanent impact. While environmental effects are likely to be minor, it should be emphasized that if operations are initiated, the probability of major impact always exists given the occasional carelessness of individuals. A proper risk assessment analysis should be required and a plan for risk management promulgated prior to any operations being started.

Offshore Hydrocarbon Development

The initial stage of geophysical surveys would have little impact. Seismic exploration involves the generation of shock waves that might damage biota, particularly those with auditory membranes, in the immediate vicinity of the vessel, but otherwise the impact would be on the same scale as that of any other comparable research vessel. Splettstoesser [1978], among others, discusses possible means of offshore development in Antarctic water.

In Antarctic waters, exploratory drilling would have

to be undertaken from special platforms capable of ice breaking and/or maneuvering and with the capability of rapid disconnection from the well (and reconnection). Impacts on the benthic biota and in the vicinity of the operation are likely to be minor though possibly severe very locally through the accidental loss of drilling muds, certain hydrocarbon pollutants associated with drilling, and discharge of effluents from the drilling platform and supply ships. Of greater consequence would be the accidental and temporarily uncontrollable release of hydrocarbons from an exploratory well due to a blowout or some other cause, particularly if this were to happen late in the season and weather or ice conditions prevented remedial action; this problem will be considered further along with tanker accidents. Shore facilities constructed at this stage would be unlikely to affect the environment any more than current activities in Antarctica [National Science Foundation, 1979].

The construction of support facilities for a producing field would have greater impact locally. Drilling of production wells in principle does not differ greatly from that for exploratory drilling. However, the wellhead hardware and pipelines to shore storage would have to be buried. Temporarily, there would be severe local impact on the biota, though it would most likely recover after construction was completed. The construction of a tank farm, associated pipelines and pumping facilities, docks and tanker loading facilities, power-generating plants, and living quarters for the construction crew and subsequent maintenance crews could have a permanent impact on the environment. There would be extensive terrain modification, dispersal of rock dust and rock material during construction, major disturbance to the permafrost regime if in a region of ice-rich permafrost, and, depending on the location, possible permanent loss of ground for breeding colonies of birds and/or seals and loss of terrestrial ecosystems and their biota. Accidental small-scale spills of fuel, lubricants, drilling muds, etc., would probably occur but have little widespread impact compared with the terrain modification for shore-based facilities.

During the subsequent production stage, small-scale accidental spills of fuel oil, waste petroleum products, sewage, or crude oil may be expected, and also accidental bilge discharges. None of these would be a major impact when compared with the rupture of storage tanks or other accidental releases that could introduce large quantities of crude oil into the environment. On land, in areas of dry permafrost, a large crude oil release could drain into the ground and down the hydraulic gradient, possibly reappearing at the surface somewhere else if suitable conditions occur. Ice-rich permafrost would inhibit penetration and keep the crude oil at or near the surface. The most volatile fractions would evaporate albeit more slowly than in temperate regions. The residual crude oil would be very viscous. All terrestrial

biota in the region of the oil spill would doubtless be destroyed or harmed. If any of the crude petroleum reached the sea, it would impact the bottom fauna and surface feeders. Seals and birds that pass through coastal waters en route to colonies on land could be seriously impacted. Dispersal at sea would be quite slow and also probably lead to the formation of high-molecular-weight globs of tarry material, or "jelly balls," that can sink and eventually accumulate on the seafloor. If the petroleum were to become entrapped under the ice, dissipation would be extremely slow, volatilization would be nil, and the potential for longer-term impact would be increased considerably. While care may be taken in all operations, the potential for a serious blowout in the initial development of a field or in the discovery stage is always present. While not a worst case scenario, the impact on the Antarctic environment over a fairly large geographical area of an Ixtoc 1 type accident deserves serious consideration [Gregory, 1982].

The Ixtoc 1 blowout off the west coast of Mexico's Yucatan peninsula flowed for 9 months from June 3, 1979, to March 23, 1980. It is reported to have flowed at an estimated rate of 30,000 barrels per day for 3 months and at a reduced rate for 6 months, releasing a total of 3.1 million barrels of oil. This accident is to date (March 1989) the largest oil spill in history. Since crude oil is a natural product, it is reasonable to assume that "mother nature" has learned how to handle it; nevertheless, it is necessary and important to assess what impact an oil release of this magnitude would have on the Antarctic environment. Given the serious operational difficulties likely to be encountered in offshore Antarctica, before cleanup or shutting off the flow from a major blowout, major damage to the environment could result. Even if only temporary, such damage would clearly impact thousands of square miles of the offshore area. The environmental implications of such an accident especially in the Ross Sea area and that along the Antarctic Peninsula deserve serious consideration prior to any drilling activity.

Normal tanker operations are unlikely to have significant impact except when collision, storm, or ice damage released crude oil into the ocean. Because of economies of operation and the greater ice-breaking capabilities of larger vessels, it is most likely that tankers would be in the VLCC class and therefore at least 250,000 tons. Crude oil released at sea would definitely affect the biota, but it is difficult to predict the impact because of a lack of data. Microbial degradation is likely to be at a lower rate than in lower latitudes because of lower temperatures. Oil floating on the sea would coat and kill most organisms at the surface and those that come to the surface periodically. Plankton would be affected directly, as would bird and seal populations through oiling and hydrocarbon toxicity.

Oil floating under the ice would degrade very slowly and have an even more severe impact on organisms.

By direct ingestion, or through feeding habits of successive trophic levels above the phytoplankton that may lead to bioconcentration, all parts of the food web may be affected. The precise effects of, or even the degree of vulnerability to, hydrocarbon coating or ingestion on breeding cycles, respiratory mechanisms, growth rates, etc., are largely unknown. *Norrell and Johnston* [1976] and *Shaw and Cheek* [1976] have reviewed the effects of oil on the microbial component of silt systems and on the benthic environment. Their work in the Arctic has applicability to the Antarctic and is worth reviewing in the context discussed herein. A major impact on sea birds is certain [*Marlins*, 1977a, b]; for other organisms the extent of the impact is uncertain. A single large-scale spill, while not likely to have a permanent effect on the total ecosystem, could under the right circumstances cause severe temporary problems locally and perhaps regionally; repeated spills would be cumulatively more damaging with the attendant possibility of chronic debilitation of the biota. Repeated accidents in the summer months, during the annual reproductive cycle, would be more serious than winter spills except in the case of the emperor penguins, which could be most vulnerable during spring. Accidents where wind, currents, and ice conditions are appropriate would lead to severe coastal impacts.

While simple in relation to that of other oceans, the Antarctic marine ecosystem by virtue of its great size probably would have adequate resilience and stability to withstand even the greatest perturbation from oil and gas exploration or exploitation. The dark winter months when birds and seals feed competitively in the pack ice and the breeding periods would be times of reduced homeostasis during which impact could be greatest. Bioconcentration perturbations would be possible at any time, most likely in plankton and pack ice communities. Such impacts may be expected to resemble those discussed for the Arctic [*Marlins*, 1977a, b].

Onshore Hydrocarbon Development

Geophysical surveys on land would require establishment of a temporary base with facilities for movement by surface or air across some distance, perhaps as much as 1500 km. There would be locally severe, if not permanent, impact caused by construction of the base, buildings for the transport system, fuel depots, and dock facilities. This is the same type of impact as for the construction of a tank farm, etc., but on a much smaller scale; it would be unlikely to exceed that of any current Antarctic base where such transportation is available. Remote field activities would involve transport of personnel and equipment and establishment of temporary camps. For shallow explosions the impacts would be

small and localized and no different from those of any current remote geological or geophysical field project.

The exploratory drilling stage would be a larger operation because of the drilling rigs and associated pipe, etc.; the need for a power source for drilling at a remote site would entail transport of considerable fuel and use of lubricants. Drilling muds and living facilities for the drilling crews on site would be required. The base site would be unlikely to exceed that of any current Antarctic station, and would have similar impacts [*Parker*, 1978a; *National Science Foundation*, 1979]. The remote field operation would involve a number of individual drilling sites within a relatively restricted area. The actual drill rig operation would probably cause severe, very local impacts, such as terrain modification, destruction of biota, possible loss of habitat for breeding colonies, and accidental spills. The Dry Valley Drilling Project activities provide a guide to the types of impact that can be expected [*Parker*, 1978a; *National Science Foundation*, 1979], although they were on a much smaller scale. An accidental uncontrollable blow-out would have a very severe impact of the type discussed under rupture of storage tanks.

Construction of facilities for a producing field would be similar to that for offshore production, with overland and underwater pipelines having impact on the surface rather than just on the seafloor as for the offshore development. Potential impacts during construction and in the producing stage would be the same as those discussed for offshore development. The greatest danger as always would be from accidents in all phases of the operation.

High Unit Value Commodity

In this case, no specific mineral or commodity is discussed because of the range of possibilities (gold, silver, chromium, platinum, etc.). Each commodity would have to be treated according to the type of occurrence (native metal, oxide, metallic sulfide) and the processing necessary for production of concentrate or refined metal to ship out. Treatment on site is not likely owing to the large amounts of energy required for processing. We assume the raw ore will be shipped for treatment elsewhere. The range of metals is broad, ranging from native gold to rich copper deposits, and could include tin, tungsten, cobalt, titanium, chromium, molybdenum, platinum group elements, or a variety of other metal or nonmetallic ores (e.g., coal). Low-grade ores such as disseminated porphyry copper deposits are excluded from consideration. A hypothetical sulfide ore is discussed in order to indicate the possible processes and their potential impacts on the environment even though we do not consider on-site processing or refining likely to occur because of the large energy requirements of these techniques. *De Wit* [1985], *de Wit and Kruger*

[this volume], and *Beike* [this volume] have done an economic evaluation of constructing a mining facility in the Dufek Massif for the platinum group elements believed to occur there.

The development through to the production stage of a mineral resource somewhat parallels that of hydrocarbon extraction. Initial field surveys using traditional geological field mapping methods and appropriate geophysical techniques are followed by exploratory (slim hole) drilling to prove the extent of the ore body. Construction of the mine and associated facilities includes haulage and developmental tunnels and shafts for access for workers and machinery to the working face, tramways, conveyor belts or other transport systems for the removal of the ore and associated waste rock, and ventilation, heating, or cooling facilities; mills for the crushing and grinding of ore; concentrating plants where physical or chemical methods yield a product suitable for a smelter; a smelter if refined or partially refined metal is to be produced; suitable storage for the product prior to shipment (this would be required for any situation); and living facilities for the mine personnel.

It is assumed that the best available technology and operating procedures will be used and that every effort would be made at every operational step to minimize impacts on the environment. This includes control of particulate (rock flour) release; control of the disposal of gangue material (waste rock), waste from concentrating processes, and furnace slag; control of gaseous pollutants; and the use of the least damaging and most efficient sewage disposal methods.

Initial field surveys are unlikely to have any greater impact on the environment than present geological programs in Antarctica [Parker, 1978a]. Exploratory drilling would have similar requirements and impact to that of onshore hydrocarbon exploratory drilling, except that there is nothing comparable to the blowout.

Construction of a mine will have locally severe, if not permanent, impacts. Mine construction produces large volumes of rock waste that would be dumped at or near the site or in the sea if adjacent. Groundwater, a frequent problem in low latitudes, would not be expected to present any difficulties in permafrost terrain unless the mining operation leads to extensive melting or extensive excavation (if depth is necessary). However, highly saline groundwater is known to exist in different coastal areas of Antarctica, and the possibility of pollution from this source deserves serious consideration; if extensive melting occurred or a large volume of saline groundwater were to be released, then the possibility of the generation of acid or toxic waste waters would be increased. Construction of the ore processing facilities, etc., would lead to terrain modification, loss of terrestrial biota, possible alteration of the local permafrost distribution, and possible loss of habitat for birds and seals near the coast. Inland, of course, there would

be no impact on living forms. The type of impact would be the same as that for construction of oil storage facilities, etc., already mentioned.

The production stage would generate a variety of impacts. Among these would be the continuous accumulation of waste rock from crushing and grinding operations. This waste would accumulate in dumps on land or it could be dumped into the sea (for coastal activities) where there would be locally severe, and possibly temporary, impact on the biota. The impacts could also be permanent. Actual mining and mechanical concentration of ore require large volumes of fresh water which in most places would have to be derived from melting snow and ice; this would impose a major increment on the power demands of the mine and thus necessitate a large generating plant. Slurries of waste material may be produced which could not be sent to settling ponds because of the cold temperatures and the need to reuse water; the separated or unseparated solid wastes would be disposed of on land or in the sea. Physical and chemical concentration and treatment of ores will likely involve the use of large volumes and a variety of special chemicals. The accidental loss and escape of these chemicals into the environment would be very harmful to the biota. Likely waste products include furnace or smelter slag and gases such as sulfur dioxide, among others.

In general, it would appear that mining a high unit value commodity would involve severe local and possibly areal impacts, mainly terrain modification and local loss of biota and habitats. It would probably not be significantly greater or more harmful than a major Antarctic scientific station in terms of impact by personnel; however, where unusual chemicals of known and those of uncertain toxicity leaked or spilled into the environment, particularly the marine environment, or where gaseous pollutants such as sulfur dioxide, which inhibits lichen growth, are discharged untreated, the potential environmental impact locally and areally could be significant. Given the facts noted above and the problems associated with construction of a major energy source, we do not feel that mineral extraction or production from Antarctic deposits is imminent.

While no mining is presently taking place, it is encouraging that consideration of regulations regarding Antarctic mineral development have been promulgated and are awaiting adoption by the countries making up the Consultative Parties to the Antarctic Treaty (ATCP). On June 2, 1988, 20 nations that are Consultative Parties to the Antarctic Treaty signed a convention that provides this regulation. The convention is an "international effort to develop rational guidelines for the management of the mineral resources of an entire continent" [Molina, 1988]. To our knowledge, as of February 1990, Australia and France had not formally agreed to and signed the convention.

The convention, when approved, will apply to the continent of Antarctica and Subantarctic islands south of 60°S latitude, the ice shelves, and the sea bed. It will be in effect when 16 of the countries making up the ATCP formally give it approval.

As noted by *Carpenter* [1988], "The Antarctic minerals treaty has tough standards . . . All minerals development, including exploratory drilling is prohibited until it has been determined that the activity won't significantly harm Antarctic and related ecosystems or degrade areas of aesthetic, historical, or scientific value. Only the passage of time will determine if such stringent terms will hold in the face of an agreement with little enforcement power behind it."

Tourism: Impact on the Antarctic Environment

Tourism is clearly an established Antarctic activity. While tourism is not a mineral resource, it is important as a "visual resource." It is also an economic resource and deserves consideration in this volume. Its scope is likely to expand in the future. The level of tourist activity in Antarctica over the last 30 years has been documented reasonably well [*Reich*, 1980; *Boswell*, 1986; *Division of Polar Programs*, 1988]. Details will not be repeated here; the interested reader is referred to the publications noted. Several documents have been written that discuss and review the trends and impact of tourism on the Antarctic environment [*National Science Foundation*, 1979; *Erize*, 1987; and *Division of Polar Programs*, 1988]. According to *Wilkerson* [1990], "Tourism and private expeditions rose to unprecedented numbers with station visits moderated in cooperation with the National Science Foundation" of the United States.

Most tourists come by sea. Antarctic cruises up to now are of two different kinds: (1) natural history cruises, conducted mostly in small vessels, and (2) more traditional entertainment cruises in larger passenger ships. Other tours arrive by plane and remain on the continent only a short time. *Erize* [1987] states that tourism is unlikely to increase much in the near future because of its high cost, risk of passenger dissatisfaction on account of bad weather, and the difficult financial situation of some countries sponsoring the trips.

Because of its closeness to South America, the majority of tourist visits have occurred on the Antarctic Peninsula; however, itineraries in the Ross Sea sector of the continent and Subantarctic islands are planned for the 1990–1991 season using Hobart, Tasmania, and Christchurch, New Zealand, as home ports. This trend is likely to continue, although the total number of tourists visiting Antarctica has dropped in the last 2 years. A few visits have been to operating research stations on the continent but not without disrupting base operations. Several countries, including the United

States, do not encourage such visits; however, one country, Chile, has erected a hotel (at Teniente Marsh Station) which provides services to visitors. *Erize* [1987] reports that a bank was opened in February 1985 at the station. Whether other countries will provide or aid in providing similar facilities is an unanswered question. Some countries welcome tourist ships and, in some cases, have provided opportunities for purchase of souvenir items such as cloth patches, shirts, stamps, caps, etc. Aside from the economic returns of these visits, early tourist ships in the Antarctic spring provide a welcome respite for overwintering personnel.

Impacts on the Antarctic environment from these activities vary greatly. Overall, the impact of tourism on the Antarctic ecosystems is limited because to date the numbers of tourists have not been large [*Erize*, 1987]. The effects of cruises that do not "land" (visual observation of the environment only) are minimal or almost nonexistent. The impact of research stations is usually on the immediate surrounding area and probably does not cause any worse effect than actual operations of the station itself. Careless tourists and visitors to breeding colonies of sea birds, seals, and other animals may temporarily cause disruptions. Control is the key in such areas. Tourist visitations anywhere in Antarctica, no matter how small, will of course produce a subtle impact on the environment. This is of some concern because given the nature of Antarctica, most visitations of any group will occur in the coastal or near-coastal areas. Lack of proper housing, services, dangers, etc., will prevent extensive visits inland for a long time, hopefully, decades. It should be noted, however, that commercial tourist visits to the interior began earlier in this decade (e.g., mountaineering expeditions to the Ellsworth Mountains). Other trips to the geographic South Pole occurred in the 1987–1988 and 1988–1989 austral summers.

The potential of large-scale commercial tourism (a few such visits have already occurred) is generating considerable concern among Antarctic Treaty nations. Such activities may not be readily amenable to management [*Division of Polar Programs*, 1988]. The primary concerns are Antarctic tourist activities that (1) may generate recognized impacts to the environment or biota of Antarctica and its surrounding waters, (2) contravene the requirements of the Antarctic Treaty and the laws of specific countries (e.g., U.S. Antarctic Conservation Act of 1978), and (3) affect research activities.

Tour operators and tourists to Antarctica generate waste materials and substances that, if not properly handled, can degrade the environment. Among these materials are human waste, plastic wastes, fuel spills, and packaging of all types associated with human activity. Tourists also can disturb breeding activity as noted earlier, impede the normal progress of local fauna, and

destroy limited plant or soil habitats. Other more subtle impacts may occur of which we are still not aware.

We strongly urge all countries (the world community) from which tourist visits to Antarctica originate to adopt the terms of the Antarctic Treaty and the recommendations approved by its Consultative Parties that bear on the issue of tourism and its impact on the Antarctic environment.

Recommendations include the following: (1) measures for the conservation of Antarctic fauna and flora, establishing Antarctica as a special conservation area and declaring guidelines regarding fauna and flora; (2) that governments make known certain provisions of the accepted principles and relevant provisions of the Antarctic Treaty as it is applied to the environment. These include the following [*Division of Polar Programs*, 1988]:

1. The killing, wounding, capturing, or molesting of any native mammal or bird is prohibited except in an emergency.
2. Every effort shall be made to minimize harmful interference with the normal living conditions of any native mammal or bird.
3. Fur seals and Ross seals are Specially Protected Species.
4. Certain areas of outstanding scientific interests have been designated as Specially Protected Areas in order to preserve their unique natural ecological system. No person may enter such an area except by special permit.
5. No species of animal or plant not indigenous to the Antarctic Treaty area may be brought into the area except by permit.
6. Every effort should be made to prevent damage or destruction to any historic monument.
7. Permission should be sought in advance to visit Sites of Special Scientific Interest, which have been set aside to allow for scientific investigations free from accidental interference.

Other helpful guidelines for visitors to the Antarctic are provided by *Division of Polar Programs* [1988, pp. 16–17]. These and other environmental guidelines are being practiced by the tourist companies operating out of the U.S.; printed guidelines are distributed before each cruise to all passengers, and the staff naturalist-lecturers aid in enforcing these guidelines at all shore stops.

Antarctica and its surrounding islands are among the few places in the world which are still relatively unchanged by human activities. Scientists still know very little about the ecological situation in the Antarctic. At the present early stage in research on these matters, some restrictions and precautions may seem unnecessarily harsh, but preliminary studies indicate the need for great caution.

By following these few simple requests, anyone can help preserve the unique environment of the Antarctic.

1. Avoid disturbing wildlife; in particular, do not walk on vegetation, touch or handle birds or seals, startle or chase any bird from its nest, or wander indiscriminately through penguin or other bird colonies.

2. Litter of all types must be kept to a minimum. Retain all litter (film wrappers, tissue, food scraps, tins, lotion bottles, etc.) in a bag or pocket to be disposed of on board your ship. Avoid throwing metal cans and other trash off the ship near land.

3. Do not use sporting guns.

4. Do not introduce plants or animals into the Antarctic.

5. Do not collect eggs or fossils.

6. Do not enter any of the Specially Protected Areas, and avoid Sites of Special Scientific Interest.

We also urge that all signatory countries to the Antarctic Treaty and the Consultative Parties enact provisions similar to those in the Antarctic Conservation Act of 1978 (U.S.) which could make the following unlawful: to take within Antarctica any native mammal or bird; to collect a native plant in a Specially Protected Area; to enter any Specially Protected Area or to enter certain Sites of Special Scientific Interest; to possess, sell, offer for sale, deliver, receive, carry, transport, or ship any native plant collected in a Specially Protected Area or any native mammal or bird; to introduce into Antarctica any animal or plant not indigenous to Antarctica.

Exceptions are allowed under emergency circumstances to prevent the loss of human life, to provide food, and by permit for certain scientific applications.

If the principles and guidelines presented here are followed by all tourists to Antarctica, then tourism will have a negligible impact on the Antarctic environment. If not, the impacts can and will multiply to the extent that they can alter and/or destroy the environment as it exists by the end of the century.

SUMMARY

Impacts and the assessment of impacts vary greatly. In evaluating the consequences of exploitation, the impact should be assessed with respect to (1) probability of occurrence; (2) magnitude and the type of impact; (3) duration of impact and of the result of the impact; (4) the economic, cultural, and aesthetic importance of the site disturbed; and (5) the probability of being able to recognize that impact has occurred.

These are not arranged in an order of implied relative impact. To the extent that impacts can be assessed in scientific terms, there can be little doubt that severe local impacts would result from resource extraction. The terrain would be modified, local terrestrial biota destroyed, and possibly breeding grounds for vertebrate

animals eliminated. The true terrestrial and aquatic ecosystems probably have reduced homeostasis relative to the ocean and hence are less resilient and stable. However, the terrestrial and aquatic ecosystem, being younger, may also be in an intermediate stage of succession where cyclic and noncyclic changes, invasion and colonization, competitive exclusion, and niche filling are readily occurring. These features characterize natural low homeostasis and also make impact identification difficult. Probably the more diversified, more elaborate ecosystems of the lower-latitude maritime Antarctic will be less vulnerable to permanent perturbation than the ecosystems of the continental dry valleys. Inland (more than 40 km) the impact on the biota will be nil except for atmospheric pollutants.

The complete loss of land forms, soil types, and terrestrial biota seems an unlikely event in any Antarctic habitat because of the regional distribution of these features. However, the cold desert lakes appear to be more vulnerable (and possibly unique) and need special protection. The circum-Antarctic distribution of birds and marine mammals makes the complete loss of any one species unlikely as a result of resource development at any one place along the coast. Specially Protected Areas or Sites of Special Scientific Interest would assure the survival of species even if there was considerable development on land. Similarly, impacts on the marine environment, on the basis of present knowledge, would not eliminate any species; repeated major hydrocarbon spills could be very serious and might well bring about large reductions in populations but should not prevent recovery given sufficient time, provided no permanent intervention had taken place.

On the basis of present knowledge, there appears to be no compelling scientific reason for banning resource exploitation provided sufficient Specially Protected Areas are established and exploration, development, production, and exploitation are conducted with all necessary precautions to minimize impacts on the environment. Without such precautions, the scale of impact will, of course, be orders of magnitude greater. And even if all precautions are taken, no absolute guarantees can be given against either breakdown of machinery and installations or against human failing. Accidents can and will happen. What will be critically needed in all cases is a careful and complete risk assessment for each mining operation projected and a meaningful program of risk management once the assessment has been made.

We recognize the value of Antarctica for baseline studies to provide data against which man-induced changes can be evaluated. Nothing should be done to diminish the value of the continent for such studies without serious consideration of the consequences. Similarly, we note that basic processes in the marine and terrestrial ecosystems are still poorly known, and

nothing should be done that will cause permanent damage to the biological integrity of any region of the continent.

While we recognize the aesthetic and scientific value in preserving all varieties of primitive or unusual soils and soil microbial communities widespread in Antarctica, a reasonable number of areas set aside as Sites of Special Scientific Interest or Specially Protected Areas should protect these soil types from total destruction and thus eliminate the need to close all regions wherein Antarctic soils are known to occur. Indeed, some Antarctic soils are already substantially disturbed by previous scientific and logistic support activities [Cameron *et al.*, 1970; Ugolini, 1970, 1977; Parker *et al.*, 1982].

Furthermore, and this cannot be emphasized too strongly, insufficient information on biologically important interreactions is available to enable management and policy decisions to be made. This is discussed in greater detail by Holdgate and Tinker [1979].

Unperturbed Antarctic ecosystems are poorly understood, and how environmental impacts may affect these ecosystems is largely unknown. It is conceivable that qualitative differences, as yet unrecognized, render the Antarctic ecosystems more susceptible to permanent damage than ecosystems elsewhere. The large body of data from Arctic studies [e.g., Hood and Burrell, 1976] may not be applicable to impact assessment on Antarctic ecosystems. Perhaps what is needed is a pilot plant project for hydrocarbon and high-value mineral exploitation with appropriate impact monitoring before major exploitation of any alleged resources is permitted.

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CONVENTION ON THE REGULATION OF ANTARCTIC MINERAL RESOURCE ACTIVITIES

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CONVENTION OUTLINE

In June 1988 the Special Consultative Meeting on Antarctic Mineral Resources concluded more than 5 years of negotiations between the Consultative Parties to the Antarctic Treaty with agreement on the text of the Convention on the Regulation of Antarctic Mineral Resource Activities. The Convention provides an exclusive framework for the regulation of prospecting and the licensing of exploration and development in the area south of 60°S. Licenses can only be obtained by States Parties to the Convention or by Operators sponsored by such States.

The Convention provides for institutions to regulate Antarctic mineral resource activities. The Commission is to be composed of the Antarctic Treaty Consultative Parties. The Consultative Parties are those countries which were original parties to that Treaty, together with the other parties to that Treaty which are carrying out substantial scientific research activity in Antarctica. The Commission also includes any other Convention party satisfying a substantial research activity test or sponsoring specific resource activities. It has a lengthy list of functions of rule making, decision, and supervision.

When an area has been identified for possible exploration and development, a Regulatory Committee is to be established for that area with respect to a particular resource or resources. The functions of the Regulatory Committee include the consideration and approval of applications for exploration and development. The Regulatory Committee prescribes a Management Scheme for the specified resources in a block. The Scheme will provide for many of the matters of central concern to mining, such as financial obligations of Operators, performance requirements, and enforcement of the Scheme (Article 47). Since it is the Regulatory Committees, rather than the Commission, which make most of the crucial decisions for miners, the membership and voting procedures of these Committees were key issues at the negotiations.

The Scientific, Technical, and Environmental Advi-

sory Committee, consisting of all parties to the Convention, advises the Commission and the Regulatory Committees on the scientific, technical, and, in particular, the environmental aspects of decision making. The Advisory Committee's views must be taken into account by the bodies it advises, but the advice is not binding.

Decisions about Antarctic mineral resource activities have to comply with principles designed to ensure that the activities will not cause serious damage to the environment (Article 4). Other elements of the Convention include detailed liability rules and provision for dispute settlement.

CONVENTION NEGOTIATION

The Convention is an integral part of the Antarctic Treaty System (Article 2(1)) and can only be understood in the light of that System. Its basis is the Antarctic Treaty and measures agreed under it. The 12 nations active in Antarctic scientific research in the International Geophysical Year, which ended in 1958, consisted of the seven claimants to Antarctic territory, the United States and the USSR (which did not recognize claims and reserved their rights to make future claims), and three nonclaimants (which did not recognize claims). The central feature of the Treaty, Article IV, purports to freeze claims as long as the Treaty is in force [Auburn, 1982]. The Treaty also provides for the freedom of scientific investigation, use of the Treaty Area for peaceful purposes, inspection at any time by observers designated by the Consultative Parties, and a ban on nuclear explosions.

The Antarctic Treaty was designed as a framework for avoiding conflict and safeguarding scientific research. It was not intended to provide a definitive solution to the underlying claims disputes. The Treaty is brief, consisting of only 14 articles. It deliberately avoided establishing any formal organization, owing to claimants' fears of internationalization. However, there is provision in Article IX of the Treaty for meetings of

the Consultative Parties to adopt measures which enter into force when approved by all the governments concerned. Such Antarctic Treaty Consultative Meetings are usually held at 2-year intervals. The measures adopted at Consultative Meetings, termed recommendations, are the regional substitute for laws. The Treaty, recommendations, and other agreements negotiated by the Consultative Parties are a closely integrated network of obligations constituting the Antarctic Treaty System.

In 1964 the Agreed Measures for the Conservation of Antarctic Fauna and Flora were drafted in the form of a recommendation (Recommendation III-VIII and related measures). In 1972 the first independent treaty was negotiated, the Convention for the Conservation of Antarctic Seals. Although regular commercial sealing has not yet been reintroduced, the Sealing Convention was a landmark in regulating a potential resource. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), concluded in 1980, went much further. It provides for the conservation and rational use of all living marine organisms south of the Antarctic Convergence, regardless of whether they are exploited or even exploitable. The CCAMLR Commission and Scientific Committee have been in operation since 1982 and have accumulated considerable experience in the practical administration of an Antarctic resource regime, including the adoption of conservation measures to restrict the catch of overfished species [*Commission for the Conservation of Antarctic Marine Living Resources*, 1987]. With a total Antarctic take of 545,000 tonnes in the 1986/1987 season [*CCAMLR Newsletter*, 1987] the fishery regulated by CCAMLR is a substantial current resource with a potential for multifold expansion.

Although the first recommendation to study Antarctic minerals issues was agreed upon in 1972, it was only in 1977 that major decisions were reached in the form of several principles: (1) the Consultative Parties were to continue to play an active role in dealing with Antarctic mineral resources; (2) the Treaty should be maintained in its entirety; (3) the Antarctic environment and its dependent ecosystems must be protected, as a basic consideration; and (4) the interests of all mankind in Antarctica should not be prejudiced (Recommendation IX-1). Consultative Parties' nationals and other States were urged to refrain from exploration of Antarctic mineral resources while timely progress was being made toward an agreed regime. The latter provisions, termed "voluntary restraint" by some countries and a "moratorium" by others, were intended to prevent a race to locate promising resource areas and the consequent possibility of wrecking the negotiations.

In 1981 it was decided to convene a Special Consultative Meeting to negotiate a minerals regime as a matter of urgency (Recommendation IX-1). In addition to the

1977 principles, the regime was to specifically safeguard Article IV of the Antarctic Treaty. Further environmental principles included assessing the possible impact of activities on the environment to provide for informed decision making, determining whether activities would be acceptable, and establishing, as an important part of the regime, rules to protect the Antarctic environment.

The negotiating process consisted of 12 formal sessions of the Special Consultative Meeting under the chairmanship of Chris Beeby of New Zealand, together with personal consultations by Beeby with the heads of delegations, leading to the production of negotiating texts, starting with Beeby I in 1983 [*Joyner*, 1987]. The negotiations took place between the Consultative Parties.

A number of groupings emerged. Perhaps the most important for the internal accommodation was the division of views between claimants and nonclaimants. Other interests included those of countries concerned with mining directly, as distinct from those with a more distant mining interest or having a primary concern with conservation.

While the negotiations were taking place, Malaysia and Antigua and Barbuda moved to have Antarctica placed on the agenda of the General Assembly of the United Nations in 1983 [*Beck*, 1986]. This led to a Study Report by the Secretary-General in 1984 [*Secretary-General of the United Nations*, 1984]. In 1986 the General Assembly called on the Consultative Parties to impose a moratorium on the minerals negotiations until all members of the international community could participate in the negotiations. The Consultative Parties either abstained or did not participate in the voting on this resolution, thus emphasizing their strong opposition to it. A parallel resolution reiterated a call for the exclusion of South Africa from Consultative Meetings. Similar resolutions were put forward in 1987 [*Kimball*, 1987]. The underlying theme of the Malaysian initiative was that Antarctica should be the common heritage of all mankind, subject to a regime similar to that of the deep seabed [*Auburn*, 1984b]. Although this pressure for an external accommodation between the Consultative Parties and non-Treaty countries did have some early results, such as granting observer status at consultative meetings to Non-Contracting Parties and inviting leading developing countries to become Consultative Parties, the U.N. resolutions themselves appeared to have little direct impact on the text of the minerals regime. What they may have done was to put more pressure on the Consultative Parties to finalize the Convention.

STRUCTURE: COMMISSION

There are to be three categories of membership of the Commission (Article 18(2)): first, each Convention

Party which was a Treaty Consultative Party on November 25, 1988; second, every other Party to the Convention during such time as it is actively engaged in substantial scientific, technical, or environmental research in the area covered by the Convention, provided that the research is directly relevant to decisions about mineral resource activities; and third, any other Convention Party sponsoring exploration or development, during such time as the relevant Management Scheme is in force.

The first category reinforces the position of existing Consultative Parties. As in the Antarctic Treaty and CCAMLR, their Commission membership does not require any activity at all and is permanent. Some of the harshest criticism of the developing countries at the U.N. was directed at the preferential position of the Consultative Parties [Lagoni, 1986]. Yet this situation has been further entrenched in the minerals Convention. This status is underlined by the requirement in the second category of substantial research directly relevant to resource decisions. The words "substantial scientific research" (Article 18(2)(b)) are taken from Article IX(2) of the Antarctic Treaty. In that context, the words have been interpreted as requiring the establishment of a permanent scientific station in Antarctica [Auburn, 1982]. Assuming that an analogous interpretation will be placed on the Convention, the effect would be to impose a Commission membership "fee" costing several million dollars and so putting membership out of reach of many developing countries.

The functions of the Commission are listed in considerable detail (Article 21(1)). Some of its tasks are adopting measures to protect the Antarctic environment and to promote safe exploration and development; determining whether to identify an area for exploration and development; adopting measures on the confidentiality of commercial data and information; adopting general measures on the suspension, modification, and cancellation of Management Schemes by Regulatory Committees; making budgetary decisions; prescribing fees and levies; determining the disposal of surplus revenues. Most of the Commission's functions are quite specific. It is given only a small selection of the crucial decisions, general environmental measures, budget, and opening of areas. As will appear later, most of the decisions of concern to miners and claimants will be made in the Regulatory Committees.

Decisions of the Commission on matters of substance require a three-quarters majority. Assuming 20 Consultative Parties as members, at least two claimants would have to vote in favor of a substantive motion. However, consensus is required for budget matters, measures on nondiscrimination, and the decision to identify an area for exploration and development. Therefore two of the few major functions given to the Commission effectively require unanimity.

STRUCTURE: REGULATORY COMMITTEE

Each Regulatory Committee will have 10 members chosen by the Commission (Article 29(2)) and consisting of (1) the claimants (if any) for the relevant area; (2) additional claimants, nominated by the area claimants, to bring the total of claimants on the Committee to four; (3) the United States and the Soviet Union; (4) four nonclaimants; and (5) in two cases the Regulatory Committee will be expanded from 10 to 11 members. If a Commission member, which is not a member of the Regulatory Committee under the previous headings, has sponsored prospecting in the identified area and requested that the area be identified for exploration and development, that country shall be a member of the Regulatory Committee until an application for an exploration permit is lodged. A Party which is not a member of the Regulatory Committee and lodges an exploration application shall be a member for consideration of the application and remains a member as long as the resultant Management Scheme is in force (Article 29(6)).

In addition to these requirements, the Commission shall ensure that the Regulatory Committee includes, within the usual 10 Committee members, Commission members which have contributed substantial scientific, technical, or environmental information relevant to the identification of the area (Article 29(3)(a)). The Commission is to ensure adequate and equitable representation of developing country Commission members, having regard to the balance between developed and developing country Commission members. In any case, the Committee must include at least three developing countries which are members of the Commission (Article 29(3)(b)).

Even without the functions and voting procedures, it is apparent that the membership of the Regulatory Committees is a vital part of the internal accommodation between the various interests of the Consultative Parties. In June 1988 there were 20 Consultative Parties, six of which were developing countries. The minimum percentage of developing State members (usually 30%) is presumably based on this ratio. Argentina and Chile are guaranteed membership if the area covers part of their claims. The combined requirements for four out of seven claimants and three out of six developing countries mean that those countries also have a much greater chance of being members of the Regulatory Committees outside their areas. If the two countries are not selected for membership of the Committee, then three of the four nonclaimant members would have to be selected from the four remaining developing countries. Even this could not be done frequently because representation of the developing countries has to be equitable and membership should be rotated (Article 29(3)(b) and 29(3)(c)).

Even if both Argentina and Chile are members, a further developing State has to take one of the four nonclaimant positions. This would leave three non-

claimant positions to be divided among 10 countries. So developed nonclaimants with a strong record of activity in the area could be excluded. Japan and West Germany were particularly concerned at this possibility, which is now covered in part by the membership category of providers of substantial information relevant to identification of the area (Article 29(3)(a)).

The strong representation of claimants in the Regulatory Committee has been seen as some form of recognition of their rights [ECO, 1988a]. This is not meant in the legal sense, because of the saving for Article IV of the Treaty in the Convention provision on Regulatory Committee membership (Article 29(7) and elsewhere). However, special priority is given to claimants in membership and is further strengthened by the decision-making procedures of the Committee.

The Committee will make substantive decisions with a majority of two thirds of the members present and voting (Article 32(3)). This means that one of the four claimants will have to vote in favor. Since the claimants for the area concerned nominate the other claimant members, there is a likelihood of deals between claimants for mutual support in different Regulatory Committees.

Specified crucial decisions require a qualified two-thirds majority. For approval of a Management Scheme (which also constitutes authorization of exploration) and approval of development, that majority must include a simple majority of the four claimants present and voting and also a simple majority of the other six members present and voting. The first Beeby draft gave the claimants (and the Sponsor State) a veto over adoption of the Management Scheme. The veto has disappeared. But one can assume that all Committee members will be present to vote on such important decisions. If there was only one area claimant and it voted against approval, then the decision could only be passed if the other three claimants (all nominated by the area claimant) voted in favor. Again, the nomination of other claimants for Committee membership is an incentive for mutual arrangements for bloc voting by claimants.

The Regulatory Committee's adoption of guidelines requires that the two-thirds majority include half the claimants present and voting and half the other six States present and voting. This increases the pressure for deals between claimants for different areas.

The effect of the Committee's decision-making procedures is to enhance the protection of the interests of specific groups of countries, especially the claimants and the mining nations. It will pressure these groups into some form of solidarity. This may well give rise to agreements on voting intended to support national interests at the expense of the wider principles of the Convention, such as the protection of the environment.

The functions of the Regulatory Committee include

the consideration and approval of applications for exploration and development permits, the approval, suspension and cancellation of Management Schemes, monitoring, and inspection (Article 31). Since the Management Scheme, as will be shown later, gives the Regulatory Committee the power to prescribe most of the conditions vital to Operators, the Committee's functions are more important to Operators than are those of the Commission. Furthermore, the functions are stated in general terms requiring the making of specific rules. Apparently, claimants and promising nations desired this maximization of power of the Regulatory Committee at the expense of the Commission [Antarctic and Southern Ocean Coalition, 1987]. They will have much more influence in the 10-member Regulatory Committees whose membership and decision making favor claimants in particular than in the Commission with an assumed membership of at least 20.

Although the area claimants do have a preferred position in the Regulatory Committee, they had asked for even more. They did not achieve their demands for a veto over the adoption of the Management Scheme. Nor did they obtain the proposed small subcommittee of the area claimant and two others to draft the Scheme.

Here it is apparent that the Regulatory Committees will have a monopoly of most of the vital decisions. There are other examples. The Commission can review the Management Scheme or issue of a development permit for consistency with its decision to identify the area. But even this limited right of review can only lead to a request to the Regulatory Committee to reconsider its decision (Article 49). The Management Scheme is the centerpiece of exploration and development. It is prepared and adopted by the Regulatory Committee. The Commission has no right to change the Scheme in any way, even if the Scheme is contrary to the Convention itself.

The subordinate role of the Commission is further emphasized in other areas. The Regulatory Committee has sole jurisdiction over applications for development permits, with no role being given to the Commission (Article 54). It is the Regulatory Committee which monitors Operators' compliance with Management Schemes. Its sole obligation to the Commission in this respect is to inform it "as appropriate" (Article 52(3)).

STRUCTURE: ADVISORY COMMITTEE

It will be recalled that the guidelines for negotiating the regime included the protection of the Antarctic environment as a basic consideration. The Convention contains elaborate provisions to protect the environment in the form of binding principles (Article 4) and mechanisms to implement them. It is the task of the Advisory Committee to provide the necessary scientific, technical, and environmental advice to the Commission

and the Regulatory Committees. The Advisory Committee is the only permanent body with membership open to all Parties (Article 23(2)). This open structure is stressed by the granting of observer status to all Parties to the Treaty and CCAMLR which are not Parties to the minerals Convention. In considering the practical effectiveness of the Convention's provisions for protecting the environment, the powers and capacities of the Advisory Committee are of considerable importance.

Since the Advisory Committee's opinions are not binding, they are presented in the form of a report reflecting the conclusions reached and all views expressed by members (Article 27). The Committee's functions include advising the Regulatory Committees on the implementation of the basic environmental principles and on guidelines, examination of exploration applications, Management Schemes, and development applications.

In providing advice at the stages of identifying an area, considering exploration and development applications, and Management Schemes, the Committee shall undertake a comprehensive environmental and technical assessment of the proposed actions. The range of considerations in such assessments is very wide, extending to indirect and cumulative impacts, the probability of accidents, and their environmental consequences (Article 26(4)).

The Committee does play an important role in the regime. However, its functions are purely advisory. It does not have the right to ensure that after its advice has been adopted it is actually followed. Both the Commission and the Regulatory Committees can nominate observers to carry out inspections (Article 12(1)(b)), but the Advisory Committee cannot do so. The fifth version of the Beeby draft, as late as 1987, gave the Committee the function of monitoring exploration and development. Even though this was in conjunction with the Regulatory Committee and did not give the Advisory Committee any say in the actual enforcement of Management Schemes, it was not to become part of the Convention. Monitoring of compliance with the Management Scheme is now the sole preserve of the Regulatory Committee, which provides information on monitoring to the Advisory Committee as appropriate (Article 52(3)).

Looking at the past experience of the Antarctic System with similar committees (the Scientific Committee on Antarctic Research (SCAR) which advises the Consultative Parties to the Treaty and the Scientific Committee of CCAMLR), it could be predicted that such a body will not itself carry out research activities. This is because the nations concerned wish to do so under their own national programs. They do not want to give such advisory bodies the substantial funds needed for large-scale research, and they do not intend the Advisory

Committee to be in any sense a decision-making body with real power.

The subordinate position of the Advisory Committee is not confined to decision making. In examining exploration applications, the Regulatory Committee must take full account of the views of the Advisory Committee. However, the Regulatory Committee only has to refer to the Advisory Committee such parts of the application as are necessary for it to provide advice (Article 45(3)). The same applies to development applications (Article 54(6)). The decision on what is necessary rests with the Regulatory Committee, enabling it to restrict the information available as a basis for environmental and other advice. Presumably, the entire application is not to be made available owing to fears regarding confidentiality. It is not clear that such fears are justified, because any Party can attend Regulatory Committee meetings as an observer (Article 30(4)) and all Parties are members of the Advisory Committee.

While it advises the Regulatory Committee on the Management Scheme (Article 26(2)(b)(ii)), the Advisory Committee has no right to review the Scheme. The Advisory Committee has no direct say in its own funding. Even for the disposition of surplus revenues to promote scientific research, the decisions rest solely with the Commission (Article 35(7)(a)). On analysis of the Convention, in light of the past experience of the Antarctic System, it would appear that the Advisory Committee has been burdened with a formidable series of tasks but has not been given any compliance or decision-making role. Nor does it seem that it will have the financial resources or political backing to carry out the research needed to form a basis for its advice.

ACTIVITIES: PROSPECTING

The Convention applies to "Antarctic mineral resource activities," which are defined as prospecting, exploration, and development, but excluding scientific research within the meaning of the Antarctic Treaty (Article 1(7)). "Prospecting" means activities, including logistic support, aimed at identifying areas of mineral resource potential for possible exploration and development (Article 1(8)). It includes geological, geochemical, and geophysical investigations and remote sensing and sampling. Dredging and excavation are excluded, except for small-scale samples. Shallow drilling to a depth of 25 m or such depth as the Commission may permit is covered, but other forms of drilling are not.

Prospecting must comply with the Convention and measures made under it, but authorization is not needed. The Sponsoring State must notify the Commission 9 months before prospecting commences. The notification must identify the general area and the resources (broadly) and methods used, provide an environmental impact assessment, and describe measures to

avoid harmful environmental consequences (Article 37(7)). If prospecting is thought to be inconsistent with the Convention or measures made under it, the Commission may adopt generally applicable measures requiring suitable modification of the activities (Article 38).

Article II of the Antarctic Treaty preserves the freedom of scientific investigation in Antarctica. The Convention clearly indicates that this must continue, both in the definition quoted above and in Articles 10 (consistency with the Antarctic Treaty) and 15 (respect for other uses). However, neither the Treaty nor the Convention defines what activities constitute scientific investigation. It has been argued that some seismic surveys carried out by Consultative Parties could be classified as the initial stages of mineral investigations [Auburn, 1984a]. Some delegations to the mineral negotiations argued that prospecting should not be regulated because there is no difference between prospecting and scientific activity [ECO, 1984]. This difficulty is apparent in the definition of prospecting which applies to some activities already carried out under the Antarctic Treaty as scientific investigation. Although prospecting does not require a license, the notice and information demands are a substantial and expensive burden which could be circumvented by the assertion that the activity is scientific investigation under the Treaty. The Consultative Parties have themselves published Guidelines for Scientific Drilling emphasizing the potential risk to the Antarctic environment which drilling could cause by releasing hydrocarbons (Recommendation XIV-3).

Environmental groups contended that prospecting should require a permit and more stringent oversight because it could lead to substantial damage to the environment [ECO, 1984]. The decision not to require licensing assumes that this likelihood is small. Yet it is noteworthy that there is a specific liability provision covering prospecting (Article 8(10)).

ACTIVITIES: SPECIAL MEETING OF PARTIES AND IDENTIFYING AREA

Before exploration applications can be considered, the Commission must decide whether to identify the area concerned. A Special Meeting of all Parties to the Convention advises the Commission whether this would be consistent with the Convention (Article 40(3)). The Commission must take full account of the views expressed and give special weight to the conclusions (Article 41(1)). Originally, the Special Meeting of Parties was conceived as a decision-making body. As it would then have been the only institution in which the ordinary Parties had a part in a binding decision, this was seen as a concession to the criticisms of the Non-Consultative Parties that they were denied any significant role in the negotiations and the regime. It would also have gone

some way to meet U.N. criticisms of the Consultative Parties as a privileged club. But since most Consultative Parties opposed even this minor concession, it was withdrawn.

Any Party can request the Commission to identify an area for exploration and development of a specific mineral or minerals by submitting a notification containing details of the area, the resources, the physical and environmental characteristics of the area, the likely scale and methods involved, and a detailed environmental impact assessment (Article 39). The Commission's decision, taking full account of the views of the Advisory Committee and Special Meeting of Parties, must ensure the area is a coherent unit for resource management. So it is possible for one area to cover parts of two claims, with consequent effects on Regulatory Committee membership. General operational guidelines, including maximum block size, may be prescribed (Article 41). The Commission shall specify the resource or resources for which the area is identified. So there could be two Regulatory Committees for one geographical area.

One of the Commission's major duties in identifying an area is to ensure that identification is consistent with the Convention. This requires, *inter alia*, that the basic principles of Article 4 have been complied with. The Commission's decision on this issue is by consensus. Since the request for identification of the area will usually be submitted by a State intending to sponsor exploration, the consensus requirement allows a claimant to veto an unwanted intruder. Once the Commission has decided to open up an area, the following stages are controlled by the Regulatory Committees.

ACTIVITIES: SPONSOR AND OPERATOR

After preparatory work by the Regulatory Committee, any Party may lodge an exploration application on behalf of an Operator. If the Operator is a juridical person other than the Sponsoring State or its agency or instrumentality, there must be a substantial and genuine link between the Operator and the Sponsoring State. The link requires (1) that the Operator be established under the Sponsor's law and subject to it, (2) the Operator's management be located within the Sponsor's territory, and (3) the Operator be subject to the effective control of the Sponsor (Article 1(12)). This threefold test seems sufficiently stringent to ensure that the link will indeed be genuine and avoid problems of nationality of convenience. The difficulties of enforcement against multinational corporations are best solved by this type of test [Francioni, 1986]. The Sponsor must certify that the required link exists (Article 44(2)(d)) and recertify for the development application (Article 53(2)(c)). But in the ordinary case there is no requirement for full supporting documentation of the link. Certification applies only at the time it is given, and the same applies for the

certification of the Operator's financial capacity. So the subsequent loss of the genuine link would not apparently be the responsibility of the Sponsoring State, even though it is cause for cancellation of the Operator's permit. However, the matter could be dealt with under the Management Scheme.

Apart from lodging the application for a permit (and thus having effective control over its presentation), the Sponsoring State must be consulted in the preparation of the Management Scheme (Article 46). With some major exceptions, the Sponsor's consent is required for cancellation of a permit (Article 50). If not a Commission member, the Sponsor is entitled to membership as long as the relevant Management Scheme is in force (Article 18(2)(c)). The same applies to membership of the Regulatory Committee (Article 29(6)(b)). In specified circumstances the Sponsor is liable for some damage resulting from its failure to carry out obligations under the Convention with respect to the Operator (Article (3)(a)).

ACTIVITIES: EXPLORATION

The Regulatory Committee's first function is preparatory work (Article 43). This includes dividing the area into blocks, setting application fees and handling procedures, and determining a method of resolving competing claims. The Committee shall also adopt guidelines covering general requirements for exploration and development in its area.

On completion of this preparatory work, a Sponsoring State may lodge an application for an exploration permit (Article 44(1)). The application must contain a detailed description of the Operator and the proposed exploration and development activities. There must be an explanation of how the activities conform with the Regulatory Committee's general guidelines and, apparently, those of the Commission and the provisions of the Convention. Also a detailed assessment of environmental and other impacts is required. The Regulatory Committee must ensure the application complies with the Convention and applicable guidelines. The approval of the relevant Management Scheme is also authorization for issue of the exploration permit (Article 48).

It will be recalled that approval of the Management Scheme and of development are the two decisions of the Regulatory Committee with the most stringent voting requirements. They are closely connected. This indicates that, just as the Regulatory Committee is the most powerful institution of the Convention, so the Management Scheme is the central instrument covering exploration and development. Exploration can only be approved if the relevant Management Scheme is in force (Article 48).

Negotiation of the Management Scheme is seen as the mechanism for protecting claimants' positions. Since

the Convention has 22 general topics for setting conditions under a Scheme, there is ample room for bargaining between blocs of States. The headings include environmental protection measures, response action, performance requirements, safety, monitoring, inspection, liability, Operator's financial obligations, guarantees, enforcement, applicable law, data collection, and confidentiality (Article 47).

It was to be expected that the Convention would not contain many specific rules for resource activities projected to take place many decades in the future in a very difficult environment. However, the bargaining between the Consultative Parties has produced a system under which different legal regimes can apply to different blocks. A Management Scheme applies to a single block in relation to the resources specified. So it is quite conceivable that a single Regulatory Committee could administer several Management Schemes, each having different conditions. Varying conditions become more likely when different Regulatory Committees are involved. Multinational corporations could well consider it in their interests to seek a Sponsor (after having incorporated in that State) willing to press for the most favorable or most lenient conditions in the Management Scheme.

Area claimants are likely to attempt to harness the other three claimants on the Regulatory Committee to ensure special privileges for themselves in the Management Scheme. The structure of the Regulatory Committee invites such pressure. Operators could request Sponsors to propose relatively low limits on liability for accidents. The possibility of choice of law in the Management Scheme would allow the Operator to press for a legal system offering lengthy delays to personal accident litigants and awarding low lump sums. The Operator might even try to have a no-fault system of law selected so that the government concerned would pay for accidents.

Once the Management Scheme has been decided upon, the only form of review by the Commission is limited in scope and can only lead to a request to the Regulatory Committee to reconsider its decision (Article 49). For all practical purposes, the Commission is shut out of the crucial process of deciding on the terms of the Management Scheme.

ACTIVITIES: DEVELOPMENT

Development involves the exploitation of specific deposits (Article 1(10)). Although the Management Scheme is a prerequisite of the exploration phase, it covers development as well (Article 47). An exploration permit gives the Operator the right to explore and develop (Article 48). Although a detailed environmental assessment is required, much of the other information in the development application is merely an updating of

the previously provided details (Article 53). The major concern of the Regulatory Committee at this stage is whether the application reveals modifications to the previously presented development plans and whether previously unforeseen environmental impacts would be caused (Article 54(3)). There is a strong presumption that the development application will be granted, although it may be modified.

One can understand the desire of States interested in mining to ensure that the heavy investment in exploration will give an entitlement to development. However, the almost automatic progression from exploration to development has been heavily criticized [*Antarctic and Southern Ocean Coalition*, 1988]. It is argued that development applications should be treated in the same way as exploration applications. Having particular regard to offshore oil exploitation in Antarctic waters, this argument has some merit. The *Piper Alpha* rig disaster in the North Sea in 1988 is only the latest in a series of accidents in offshore oil fields where the climatic conditions are not as severe as the Antarctic. The Consultative Parties' own strong stress on environmental protection in the regime also indicates that development should have been considered as a separate stage. Furthermore, the substantial increase in the scale of activities at this stage represents a vastly increased hazard [*Antarctic and Southern Ocean Coalition*, 1987].

CLAIMS

The negotiation of the minerals regime raised particular problems for the seven claimant States. One of the reasons for embarking on the discussions was to close a gap in the Antarctic System [*Beeby*, 1986]. In 1991 the initial 30 years of the Antarctic Treaty finish, and it becomes an open-ended agreement. The only way to unambiguously maintain claims would have been to opt out of the Treaty, but this is impractical because claimants outside the Antarctic System would be no better off than those inside, and they would then have to take active steps to assert their claims [*Auburn*, 1984a].

The minerals negotiations were a forum for the claimants to press for concessions from the other Consultative Parties. Their initial successes were substantial, particularly in obtaining a veto by the area claimant over the adoption of the Management Scheme. But this had to be dropped. Nor did they succeed in obtaining a specific commitment to a preferential share of surplus revenues. However, the Convention carries many clear indications of the deep-seated concerns of the claimants. Their privileged position in membership and decision making in the Regulatory Committee has already been discussed, as has the Management Scheme as a means of asserting claimants' interests (*inter alia*). Article 9 of the Convention reiterates the freezing provisions of Article IV of the Treaty with suitable adapta-

tions. That Article is reinforced by the limitation that the Arbitral Tribunal is not competent to rule on sovereignty and claims issues (Article 57(4)). The provision on entry into force of the Convention has the result that each claimant must be a Party before the Convention comes into effect (Article 62(1)).

The Convention maintains the formal status quo on claims. Some concessions have been made to claimants, and more can be expected in the bargaining in Regulatory Committees. The wider possibilities of internationalization of the continent and its resources, although gaining support in the General Assembly, were not seriously considered by the claimants or the other Consultative Parties.

ENVIRONMENT

The Objectives and General Principles require the Parties to provide, in every decision and in every institution of the Convention, for specific concern with the environment (Article 2(1)). However, the Convention has an additional general provision of an innovative nature prescribing in considerable detail (Article 4) that no Antarctic mineral resource activities shall take place unless it is judged, based on assessment of possible impacts, that the activities would not cause (*inter alia*) (1) significant adverse effects on air and water quality; (2) significant changes in atmospheric, terrestrial, or marine environments; (3) significant changes in the distribution, abundance, or productivity of populations of species of fauna or flora; or (4) significant adverse effects on global or regional climate or weather patterns. Decisions about resource activities shall be based upon information adequate to enable informed judgments about possible impacts. No such activities shall take place unless this information is available for decisions relevant to those activities (Article 4(1)). No resource activities shall take place until it is judged that technology and procedures are available to provide for safe operations. Nor shall they take place unless there exists the capacity to monitor key environmental parameters and identify adverse effects and the capacity to respond effectively to accidents, especially those with potential environmental effects (Article 4(4)).

Article 4 provides for a "cascade" of principles, operative at every stage of decision making [*Kimball*, 1988]. It may be contrasted with CCAMLR which only has very generalized conservation principles (Article II, CCAMLR). The difference is that the minerals Convention contains specific and binding directions that no activities shall take place unless the required judgment is made. The burden of proof is placed upon those applying for permits. In CCAMLR, as in many conservation regimes, the burden of proof is placed on those asserting that environmental or ecological damage may occur.

Nor is there any escape clause in the minerals Convention. By contrast, the Agreed Measures for the Conservation of Antarctic Fauna and Flora prohibit harmful interference with the normal living conditions of any native mammal or bird. "Harmful interference" specifically includes the "use of explosives close to concentrations of birds." However, such use may be permitted to the minimum extent necessary for the operation of stations (Article VII(2), Agreed Measures). This gave rise to the possible argument that the killing and injuring of penguins in the French construction of the airstrip at Pointe Géologie in 1983 and onward was not contrary to this Article of the Agreed Measures (for the contrary argument, see *Greenpeace International* [1985]).

From the legal viewpoint, Article 4 of the minerals Convention is a major advance. Environmental principles progress from exhortations to binding rules. For example, the Regulatory Committee must ensure that an exploration application is consistent with the Convention (Article 45(1)(b)(i)). This means that the Sponsoring State must satisfy that Committee that Article 4 has been complied with.

It will be pointed out that the wording of Article 4 is somewhat vague. Scientists will have some difficulty in advising whether an adverse effect is "significant" or whether a risk to an area of special biological importance is "substantial." However, the principles are concerned with activities projected to take place several decades in the future, covering a variety of possible resources and using new technology in an inhospitable climate. Greater precision in wording would have been difficult to achieve for such broad principles.

Antarctica has a very extensive coastline but relatively few attractive sites for human activity. This is shown by the concentration of scientific research stations in some areas. The situation became so bad on King George Island that the Consultative Parties expressed their concern that such overcrowding could cause undue adverse environmental effects arising from cumulative impacts (Recommendation XIII-6). Public evidence of such deleterious effects of station crowding was already available at the time the recommendation was passed [Auburn, 1982]. The problem of conflicting uses exists today and would be rendered much more serious with the introduction of coastal support and storage facilities for offshore oil exploitation.

The existing system of Specially Protected Areas and Sites of Special Scientific Interest under the Treaty is safeguarded under the Convention. No mineral resource activities shall take place in such protected areas or other areas designated by the Consultative Meeting or the Commission for ecological, environmental, historic, scientific, or other reasons, except to the extent permitted by the relevant measure (Article 13). The Commission may also establish buffer zones.

The provision for protected areas is expansive. The definitions of exploration and development both specifically include logistic support (Article I(9) and I(10)). So even activities which do not raise any direct danger of environmental damage may still be prohibited in protected areas.

Environmental impact assessment is required by Article 4 and is specifically demanded for major decisions. Comprehensive assessment must be undertaken by the Advisory Committee for presenting its advice on identifying an area, the preparatory work of the Regulatory Committee, and the examination of exploration and development applications (Article 26(4)). Applicant or Sponsoring States must present environmental assessments at the stages of notification of prospecting and application for exploration and development permits.

Although the Consultative Parties have repeatedly stressed their concern for the fragile Antarctic environment, their readiness to undertake effective environmental impact assessments comparable to the U.S. legislation has not yet been proved. Although the Pointe Géologie airstrip led to no less than three environmental impact studies, the construction program was still open to serious public criticism [Auburn, 1984a]. As late as 1987, the Consultative Meeting could only agree on weak Guidelines for what was carefully called "Environmental Evaluation," lacking any provision for public input (Recommendation XIV-2). The past record of the Consultative Parties in protecting the environment has been publicly criticized in detail on a number of occasions.

The assessments presented by Sponsor States are likely to have been prepared by the Operators and reflect their views. The effectiveness of the Convention's provisions for environmental impact assessment by its own institutions can only be estimated by examining the institutions themselves. Assessment is the task of the Advisory Committee. The practical weaknesses of the Committee have already been pointed out. Environmental impact assessment, especially in the novel and complex conditions of the Antarctic, will require extensive specialist staff, substantial resources for research and investigation, funding for prolonged periods of research in Antarctica on and offshore (including expensive ship time), and a major logistic and planning effort.

An example is the advice to be requested by the Commission on identifying an area. The decision involved is a crucial environmental issue. The Advisory Committee shall meet as soon as possible after the Commission meeting convened in response to a request to identify an area has commenced. The Commission may prescribe a time limit for the provision of such advice (Article 40(1)). An indication of the potentially applicable time frame is that the Commission itself must convene within 2 months of the notification of a request

to identify an area (Article 19(2)(a)). Furthermore, the Special Meeting of Parties shall meet within 2 months of circulation of the Advisory Committee's report and shall make its own report within 21 days (Article 40(2) and 40(3)). It appears that a time frame of months is envisaged for the Advisory Committee's preparation of the environmental assessment.

The inference is that the Advisory Committee will be restricted to existing information and will not be able to mount its own independent investigations in Antarctica. This impression is strengthened by the current practice in the Antarctic System (SCAR and the CCAMLR Scientific Committee) involving modestly funded coordination of international efforts, with no independent research or logistics capacity. Further, even the information provided to the Advisory Committee may be only part of that which is available to the Regulatory Committee (Article 45(3)).

COMPLIANCE: ENFORCEMENT

Inspection under the Convention is to be carried out by observers designated by any Commission member, the Commission, or the relevant Regulatory Committee (Article 12(1)). The Management Scheme may prescribe inspection conditions (Article 47(g)) which must be consistent with the provisions of the Convention. There are indications that inspections are viewed with some concern by States interested in mining. Inspections shall be compatible and reinforce each other and shall not impose an undue burden on the stations and installations visited (Article 12(7)). In the context of an offshore Antarctic oil rig, this could enable an Operator to object to an inspection owing to adverse weather forecasts rendering transport to the rig a hazard or even on grounds of a more subjective nature. Inspection is subject to the protection afforded to data and information of commercial value (Article 16). This overriding provision would be applicable to any request for information by inspectors and substantially reduces the value of inspection.

Monitoring of Operators' compliance with Management Schemes is the responsibility of the relevant Regulatory Committee which informs the Commission and Advisory Committee as appropriate (Article 52). The Management Scheme shall prescribe monitoring conditions (Article 47(g)). The exclusion of the Advisory Committee from any active participation in this function has a number of consequences. No resource activity shall take place until it is judged that the capacity to monitor environmental and ecological matters so as to identify adverse effects exists (Article 4(4)(b)). Yet the body carrying out the monitoring will usually include the Sponsoring State, which will in all likelihood identify with the interests of the Operator. In some cases, the State will be the Operator. The State, in

turn, will mobilize its allies (for example, fellow claimants) on the Regulatory Committee to support its interests. Monitoring of the Management Scheme is done by the Regulatory Committee as a body, and this will inevitably involve political decisions. To a large degree it will be a matter of self-regulation and of doubtful effectiveness.

Compliance by Parties to the Convention with their obligations under it is dealt with by the Commission drawing the attention of that Party to the matter (Article 7(7)). A decision of this nature is a matter of substance requiring a three-quarters majority. Therefore, assuming 20 Commission members, the affected State would only have to invoke the support of 5 other members to defeat any such motion. Claimants, in particular, would benefit from a bloc approach to such matters.

Enforcement of the Management Scheme will be governed by rules in the Scheme itself (Article 47(p)). The Regulatory Committee is also the body which determines whether an Operator has complied with the Convention, measures under it, and the Management Scheme. The Committee has power to modify, suspend, or cancel the Scheme, cancel the exploration or development permit, and impose a monetary penalty (Article 51(3)). This provision highlights the primacy of the Regulatory Committee in matters directly affecting minerals activities. A two-thirds majority is required for such a decision. The sanction of automatic cancellation is applicable for the Operator's failure to maintain a genuine link with the Sponsoring State (Article 51(5)) but is not specifically applicable for a contravention of the fundamental environmental principles of Article 4.

COMPLIANCE: LIABILITY

The liability provisions of the Convention bear the marks of a hard-fought battle which is not yet concluded. The Convention imposes strict liability connected with damage to the Antarctic environment or dependent or associated ecosystems arising from Antarctic mineral resource activities (Article 8(2)).

"Damage to the Antarctic environment or dependent or associated ecosystems" is defined as any impact on living or nonliving components of the environment. However, the impact must be beyond that which is negligible or which has been assessed and judged to be acceptable pursuant to the Convention (Article 1(15)). It will be recalled that Article 4 prevents any resource activity taking place until it has been judged that the activity will not cause significant adverse effects or changes in the environment or flora and fauna. *Prima facie*, a decision that (say) exploration for offshore oil can proceed in a particular block must involve a judgment by the Regulatory Committee that any adverse impacts discussed in the detailed environmental assessment presented to it are acceptable pursuant to the

Convention. This type of damage for which there is strict liability will rarely arise. One possibility might be that the damage which actually occurs has not been considered in the impact assessment. However, this possibility can be avoided by a carefully drafted assessment (prepared by the Operator for submission to the Regulatory Committee or other body involved). The assessment would canvass even the most remotely possible forms of damage and thus ensure that there was a judgment that it was acceptable. There is no indication here that it matters whether the judgment turns out to be right or wrong.

The exceptions to strict liability were hotly contested. The Operator is not strictly liable if the cause is an event which constitutes, in the circumstances of Antarctica, a natural disaster of an exceptional character which could not reasonably have been foreseen (Article 8(4)(a)). It is argued that the unforeseeable is commonplace in the extreme weather conditions of Antarctica, and this is one of the risks of mining. The second exception is for armed conflict or terrorism which could not have been prevented by reasonable precautionary measures (Article 8(4)(b)). Terrorism is not defined, but it presumably requires some elements of political motive. Interestingly, sabotage is not an exception.

Where strict liability applies, the Sponsoring State carries residual liability if the damage would not have occurred if the Sponsoring State had carried out its Convention obligations in respect of the Operator. However, the Sponsor is liable in accordance with international law (Article 8(3)), so that strict liability may not be applied.

Further liability rules are to be elaborated in a Protocol to be adopted by the Commission by consensus (Article 8(7)). Since the liability issues not specifically covered by the Convention are of considerable importance and the Consultative Parties failed to reach agreement on them, the likelihood of consensus in the Commission on strong and effective rules may not be high. No exploration or development permit shall be issued until the Protocol is in force for the Sponsoring State (Article 8(9)). The Protocol may provide for appropriate limits on liability. A fund may be established to pay for damages above the liability limits or where a defense applies (Article 8(7)).

CONCLUSION

Beeby described the Convention as the most important political development in the region since the Antarctic Treaty was adopted [Scott, 1988]. This is clearly correct. The impact of the Convention on the Antarctic System is substantial, regardless of whether minerals are ever exploited.

The Convention closes the most obvious major gap in the Antarctic System. The Treaty deals with scientific

research and has been applied to other activities such as tourism. The Sealing Convention covers the possibility of exploiting seals, which are a major potential resource. CCAMLR regulates current and future fishing. The minerals Convention is intended to ensure that any minerals activities are controlled by the Antarctic System. The successful drafting of the Convention, despite the substantial internal differences of opinion, is a major landmark in Antarctic affairs.

In 1989, Australia and France indicated that they would not sign the minerals Convention and proposed a comprehensive Antarctic environmental protection treaty. Other Consultative Parties showed support for a similar approach. The minerals Convention requires ratification by 16 of the 20 Consultative Parties who negotiated it. The 16 must include all the States necessary to establish all the institutions of the Convention with respect to every area of Antarctica, including 5 developing and 11 developed countries (Article 62(1)). This appears to require the ratification by all claimants. If these countries maintain their position, the Convention cannot enter into force. However, other Consultative Parties strongly support the minerals Convention. There are incentives for the Consultative Parties to maintain group solidarity, so that some form of compromise may well emerge.

The Convention was negotiated despite a direct challenge from the General Assembly of the United Nations. With regard to the economic and political power of the Consultative Parties, this result is not surprising. It is noteworthy that India, a potential leader of the developing countries' challenge in the U.N., established an Antarctic base without acceding to the Treaty. But India decided to adhere to the Treaty at the same time that the General Assembly debate began, as did Brazil, another leading developing State. Together with the accession of China, these decisions indicated a judgment that the General Assembly initiative would not succeed. Therefore the conclusion of the Convention, in the face of the General Assembly's call for a moratorium on the negotiations, demonstrates that one major external challenge to the Antarctic System by the General Assembly has been rebuffed.

Not only did the Consultative Parties reject the General Assembly's views, but they did not even make any real attempt at an external accommodation with countries outside the Antarctic System. Instead, the Convention offers inducements to developing countries to become Parties and Commission members. Participation by developing countries is to be specifically encouraged (Article 6). They are entitled to at least three seats on the Regulatory Committee (Article 29(3)(b)). For the Convention to come into force, at least five developing States must be Parties (Article 62(1)). This is a continuation of the process, evident since 1983, of co-opting

major developing States to head off an external challenge.

The Convention's impact on sovereignty and claims is likely to be far reaching. On the other hand, claimants have secured for themselves a number of advantages, principally in the membership and decision making of the vital Regulatory Committees. Although they did not achieve a veto for the area claimant or a specific allocation of surplus revenue, they did succeed in obtaining other concessions in the regime.

The Convention is quite unequivocally an integral part of the Antarctic System, both in general principle (Article 2(1)) and in many basic features such as the protection of legal positions under the Antarctic Treaty (Article 9). The Consultative Parties did not seize the nettle of solving the underlying legal problems of Antarctica by internationalization, sovereignty allocation, or otherwise. There is no basic movement on this vital issue. However, 30 years have passed since the Treaty was drafted. The claims-freezing provisions in the Treaty are looking increasingly unrealistic with the passage of time. Claimants will now lock themselves into this position with its reaffirmation in the Convention.

Official government policies of countries like Australia still proclaim strong adherence to sovereignty. This discrepancy between rhetoric and reality will become increasingly apparent over time. The claimants have also committed themselves to their assertions of sovereignty in their current form. Since claimants have a privileged position in the regime, voluntary relinquishment of claims (assuming this is possible under the Antarctic System) is unlikely. Not only does the Convention continue this situation, but the fact that mineral activities are only possible in the long term is a further incentive to claimants to adhere to claims as Commission members, lest they be accused of forfeiting future rights to exploit natural resources.

As a mining agreement, the Convention offers substantial incentives to industry. A legal framework for exploitation is in place. Without it, exploration and development would have no accepted legal basis. Miners can expect the support of their Sponsoring State in the Regulatory Committee. The Sponsor is likely to enter into alliances with like-minded countries to secure a Management Scheme attractive to miners. There is some justification in Greenpeace's complaint that environmentally concerned countries like New Zealand had buckled under pressure from promining nations such as Japan, France, the United Kingdom, and the United States [Long, 1988]. Examples are the wide reach of the data confidentiality provisions and the almost automatic progression from exploration to development.

While the developing States made major gains, the Non-Consultative Parties (ordinary Antarctic Treaty Parties) gained very little. The initial reaction of the

Consultative Parties to the U.N. initiative had been an attempt to co-opt the Non-Consultative Parties by giving them observer status at Consultative Meetings. There was an expectation that they would be given a real voice in the minerals regime, and this may have accounted, in part, for the increased number of accessions to the Treaty since 1979. But the Non-Consultative Parties did not apparently have any real say in the minerals negotiations. This is reflected in the Convention. Ordinary parties are entitled to membership in two of the Convention's institutions, the Advisory Committee and Special Meeting of Parties. Both are purely advisory. To rub salt into the wound, the Special Meeting of Parties was proposed as having power to make binding decisions, but the Consultative Parties deprived the ordinary Parties of even this minor concession. As a final indignity, the ordinary Parties to the Convention may even be the reluctant targets of financial levies (Article 35(6)) to lighten the financial burden on Commission members. This general disregard for the interests of the Non-Consultative Parties reflects a feeling of the Consultative Parties that the outside pressure from the General Assembly, which stressed the lowly status of the Non-Consultative Parties, was not a real threat.

The most effective pressure on the Consultative Parties to improve the negotiating text, especially in its environmental aspects, was exerted by the nongovernmental organizations including the Antarctic and Southern Ocean Coalition, Greenpeace, the International Institute for Environment and Development, and Friends of the Earth. They ensured that the successive Beeby drafts were made public. They published ECO, a newsletter covering each phase of the negotiations with up-to-date information. They prepared briefings for the U.N. debate and detailed commentaries on specific texts and Articles. The Special Consultative Meeting carried on the negotiations on this vital international issue for 6 years, without publishing any major text or detailed material to inform the general public. It seems that countries from opposite blocs can discuss these matters with each other, but even democracies are not prepared to expose such negotiations to public debate. A particular irritant was the Consultative Parties' dismissal of critics as uninformed. There have been some recent improvements in the openness of the Antarctic System, but they have been confined to marginal or dated material.

Nongovernmental organizations complained of the laxity of the Convention's rules for the protection of the environment. The Antarctic and Southern Ocean Coalition pointed out that the Convention's provisions would be unacceptable in the domestic law of most developed countries [Scott, 1988]. This is correct, but it should be seen as a general criticism of the laxer standards of treaties, as compared to domestic legislation.

James Barnes, general counsel to the Antarctic and Southern Ocean Coalition, described the Convention as a "web of principles that lays the foundation to do things sensibly" [Sun, 1988]. By Antarctic System standards the Convention is far more stringent than its immediate predecessor, CCAMLR. The binding nature of the bans in Article 4 is a major step forward. While the Treaty Consultative Meeting is still wrestling somewhat ineffectively with environmental assessment guidelines, the Convention has specific assessment conditions at each major stage of activities. It is correct that there are major weaknesses in the environmental protection afforded by the Convention. Examples are the lack of real power of the Advisory Committee, the practical defects of the procedures for environmental assessment, and the self-regulatory aspects of monitoring. But judged by the standards of international treaties, the Convention is a significant step forward in environmental protection.

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SPECIAL REPORT ON THE ANTARCTIC MINERALS CONVENTION

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On June 2, 1988, the Convention on the Regulation of Antarctic Mineral Resource Activities was adopted by consensus in Wellington, New Zealand. It will be open for signature for one year as of November 25, 1988, following which any nation may accede to it. The Final Act of the Fourth Special Antarctic Treaty Consultative Meeting was also adopted and signed on June 2 by the 33 countries participating in the final session. The adoption of the treaty marks the end of a six-year negotiation.

The next steps are two-fold:

- states that sign the Convention must ratify it in accordance with their domestic procedures, and in the United States this will entail implementing legislation;
- a more detailed protocol must be completed covering liability and response action for environmental damages related to minerals activities.

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When could minerals development commence in Antarctica?

The Resources and the Economics

Two plausible scenarios have been advanced for possible minerals development in Antarctica:

- (1) the discovery of a giant or super-giant oilfield on the continent or in its surrounding offshore areas;
or
- (2) the discovery of a significant deposit of high-value minerals of precious or strategic value, such as gold or platinum.

Neither has yet occurred.

In evaluating the likelihood of minerals development in Antarctica, two other considerations must be taken into account: the possibility that mineral-resource-poor nations like Japan and the Federal Republic of Germany (FRG) may subsidize operations that would not produce sufficient return to be of commercial interest to private companies, and the possibility that nations with claims in Antarctica may initiate activities in their claimed territory to help substantiate these claims. In recent years the governments of Japan, FRG, France, Norway and the USSR have substantially increased their support for geophysical research in the Antarctic continental margin.

Offshore Oil

While there is credible circumstantial evidence that major offshore oil deposits may exist in the thick sedimentary basins off Antarctica like those in the Ross or Weddell Sea, none has yet been discovered. Experts indicate that a discovery of from .5 to 5 billion barrels — a giant or a super-giant oil field — would be required to attract economic interest and investment. (For comparison's sake, the Prudhoe Bay field off Alaska is estimated at 10 billion barrels, whereas reserves in the Persian Gulf are estimated at well over 500 billion barrels.) If and when discovered, the price of oil would have to be sufficiently high to justify the substantial investments in equipment and infrastructure required to extract it. One expert predicts that even if the price of oil were to return to \$40/barrel, this would be insufficient to stimulate Antarctic minerals development in the next few decades (Behrendt, 1987).

Another requirement is that the technology to operate in Antarctic ice and weather conditions would have to be operational. While there are similarities between the Arctic, where offshore oil operations have already commenced, and the Antarctic, the differences are equally important: weather and iceberg conditions in the South are less predictable than those in the North, and once extracted, Arctic oil is much nearer to large consumer markets in the North than would be the case with Antarctic oil. In addition, the kinds of artificial offshore islands employed in the Arctic would be more difficult, if not impossible, to use in the Antarctic, where the continental shelf lies under much greater water depths. Subsea production systems yet to be fully tested would be required in deeper Antarctic waters. Moreover, the July 1988 explosion and resultant deaths on the North Sea oil rig Piper Alpha, which had just been inspected by United Kingdom authorities, gives rise to increasing concern that safety standards for advanced production technologies are not yet adequate.

The possibility of finding oil in the continent of Antarctica has also been raised. Research to date yields limited evidence of such resources. And despite the difficult weather and ice conditions associated with extracting offshore oil, most experts believe that it would be even more difficult to extract oil located a mile or more beneath the Antarctic icecap.

Hard Minerals

Whereas numerous occurrences of hard minerals have been reported in Antarctica, advocates of their possible development point to the minerals potential of the Dufek Massif in Antarctica, thought to be analogous to the immense Bushveld complex of high value, strategic and precious minerals in South Africa, and the Antarctic Peninsula, thought to be analogous to Andean copper and tin deposits. These continents were all attached about 180 million years ago in the Gondwanaland supercontinent and subsequently migrated with the movement of tectonic plates. The experts stress that only a very high-value deposit would command economic interest. As with oil resources, if and when discovered in Antarctica in sufficient quantities, the major factors

*This report has not been subjected to the regular review process but is reprinted here to make it more widely available.

to be taken into account in determining whether to exploit hard minerals will be the availability of alternative sources, the value of the minerals involved, the availability of appropriate technologies, and the costs of extraction and transport to markets.

Again, lack of detailed research into the Dufek complex of minerals and the Antarctica Peninsula -- both with respect to mineral content and with respect to the extent of any mineral deposits -- makes it impossible to predict whether there are any exploitable hard minerals resources in Antarctica and if there are, when they might be economically recoverable.

Ice

Ice is technically a mineral resource. Nevertheless, when the Fourth Special ATCM commenced in 1982, there was a specific decision to exclude ice from the coverage of the regime to be negotiated. The Final Act of the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) notes that harvesting ice from the coastal region of Antarctica, particularly if land-based facilities were required, could raise some of the environmental and other issues addressed in the Convention. It records the agreement of the states at the meeting that the question of harvesting Antarctic ice should be considered by the Antarctic Treaty Consultative Parties (ATCPs) at their next regular ATCM.

What happens next?

Drafting Committee

The Drafting Committee meets in September in Australia to conform a text of the agreement in Chinese to that of the four other authentic languages in which the treaty was adopted -- English, French, Spanish, and Russian.

Signature

The CRAMRA will be open for signature for one year as of November 25, 1988. The 20 nations that took part in the final meeting of the fourth special ATCM as ATCPs have the right to sign it. These states are:

Argentina, Australia, Belgium, Brazil, Chile, China, France, German Democratic Republic, Federal Republic of Germany, India, Italy, Japan, New Zealand, Norway, Poland, South Africa, USSR, United Kingdom, United States, Uruguay.

Signature carries with it the obligation not to take any action that would defeat the object or purpose of the treaty pending its approval in accordance with that nation's domestic procedures, by ratification or other means.

Accession

After the one-year signature period, any other nation may accede to the treaty, but it must first have become party to the 1959 Antarctic Treaty. (The Antarctic Treaty is open to accession by any member of the United Nations.) Accession carries the same meaning as ratification, in that it is an expression of a nation's willingness to be bound by the treaty.

Ratification

To enter into force, the CRAMRA must be ratified by 16 of the 20 nations that adopted it by consensus on June 2, 1988, including a minimum of 11 developed and 5 developing nations. There are additional requirements that the treaty may not enter into force until ratified by all of the seven claimant nations (five developed and two developing), by the United States and the Soviet Union that maintain a basis of claim (two developed), and by at least seven additional non-claimant nations, of which three must be developing nations (Article 62 and the Final Act). Accessions by nations that were not ATCPs as of June 2, 1988, do not count toward entry into force of the treaty. Only the 20 original signatories to the treaty may technically ratify it. For them ratification conveys the expression of intent to be bound by the treaty.

Ratification in the United States

The CRAMRA will have to be submitted to the US Senate for its advice and consent by a two-thirds vote. Once approved by the Senate, the President formally ratifies (signs) it. This completes domestic ratification

procedures, although the instrument of ratification must then be conveyed to the depositary government (New Zealand) before it takes effect and is notified to other states parties.

The CRAMRA will have to be implemented by enactment of domestic legislation in the United States. This legislation will be considered in both the Senate and the House of Representatives in the US Congress, presumably at the same time that the treaty itself is considered by the Senate. While the Senate alone has jurisdiction over treaties, several committees in the Senate and the House will have jurisdiction over the implementing legislation. These will probably include the following:

- Senate Foreign Relations
- Senate Energy and Natural Resources
- Senate Commerce, Science and Transportation
- Senate Environment and Public Works
- House Foreign Affairs
- House Interior and Insular Affairs
- House Merchant Marine and Fisheries.

Does the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) open up Antarctica to minerals activities?

This question must be answered in relation to two periods:

- (1) prior to entry into force, and
- (2) after entry into force.

Prior to entry into force

The Voluntary Restraint Agreement

In the Final Act of the Fourth Special ATCM, signed on June 2, 1988 by the 33 states in attendance at the final meeting, it was agreed:

"that all States represented at the Meeting would urge their nationals and other States to refrain from Antarctic mineral resource activities as defined in the Convention pending its timely entry into force" (emphasis added).

For those familiar with what is referred to as the "voluntary restraint" clause, this represents a continuation of the policy first adopted by the Antarctic Treaty Consultative Parties (ATCPs) at their ninth ATCM in London in 1977. In Recommendation IX-1,

"they urge their nationals and other States to refrain from all exploration and exploitation of Antarctic mineral resources while making progress towards the timely adoption of an agreed regime concerning Antarctic mineral resource activities. They will thus endeavour to ensure that, pending the timely adoption of agreed solutions pertaining to exploration and exploitation of mineral resources, no activity shall be conducted to explore or exploit such resources."

Recalling the growing interest at that time in the possibility of minerals development in Antarctica, Recommendation IX-1 served both to exhort the ATCPs to refrain from exploration and exploitation, and at the same time as a warning that if progress was not being made toward the timely adoption of an agreed regime, some states might no longer voluntarily restrain such activities. In this way, they could put pressure on any state(s) that might intentionally impede agreement on a regime.

The significance of the statement in the 1988 Final Act quoted above is that it prolongs the 'voluntary restraint' agreement as long as timely progress is being made toward entry into force of the new minerals treaty. It obviously entails the same 'leverage' as in Recommendation IX-1; that is, if there is a long delay in entry into force, states may no longer feel bound to restrain potential minerals activities. The Final Act agreement goes further than Recommendation IX-1, in that it calls for restraint not just with respect to exploration

and exploitation, but also with respect to prospecting, since mineral resource activities as defined in the Convention cover prospecting, exploration, and development.

Prospecting

There has been a certain amount of debate over whether prospecting has indeed already occurred. One issue in this debate is whether prospecting falls under the original timely restraint agreement of 1977. As noted above, however, that agreement only specifically restricted exploration and exploitation, not prospecting. Absent an agreed definition of what constitutes prospecting and what constitutes exploration, there was no way to definitively identify certain types of minerals research as exploration. The new CRAMRA now defines more clearly the line between prospecting and exploration. The key point, however, is that the restraint formula adopted in the Final Act places an absolute prohibition on prospecting as long as timely progress is being made towards entry into force of the treaty.

A second issue in the prospecting debate is that it is argued that some countries have been undertaking prospecting activities, such as seismic surveys and drilling, under the guise of scientific research, which is freely permitted under the 1959 Antarctic Treaty. Yet absent any accepted distinction between prospecting and scientific research, there was no way to prohibit such activities under existing legal agreements. The only distinction possible is that under the Antarctic Treaty, the results of scientific research have to be made freely available. To the extent that nations party to the Antarctic Treaty were not making the results of their research freely available, they were arguably in violation of the Antarctic Treaty. Nevertheless, there continue to be differing views as to the level of detail to be reported and the time periods within which these results must be made freely available. Thus, some nations believe that the raw data should be freely available, whereas others maintain that publication of research reports is sufficient. Moreover, in that it takes time for scientists to work up the results of their research, there are differing views as to what constitutes a reasonable period within which the research reports must be published. By defining prospecting as activities "aimed at identifying areas of mineral resource potential for possible exploration and development" (Article I), the CRAMRA should preclude activities covered by this definition prior to its entry into force, regardless of whether or not they had previously been carried out as scientific research. If there is any question as to whether the activities might constitute prospecting under the minerals treaty, the burden will lie with the state concerned to make doubly sure that the results are freely available.

In addition, under the CRAMRA entities conducting prospecting are permitted to retain data and information of commercial value for defined periods of time. As this is not possible with scientific research conducted pursuant to the Antarctic Treaty, potential prospectors are unlikely to run the risk of engaging in any 'questionable' scientific research that may be viewed as prospecting prior to entry into force of the CRAMRA, for they could lose their proprietary rights to this data.

The third issue in this prospecting debate is over whether offshore research, as opposed to that on the Antarctic continent and ice shelves, is indeed subject to the Antarctic Treaty regime requiring that results be freely available, or whether it constitutes an exercise of the high seas freedom of scientific research. The Japanese, for example, have taken the view that neither the requirement to publish research results (Article III of the Antarctic Treaty) nor the 'voluntary restraint' agreement (Recommendation IX-1) apply to their offshore research activities. The CRAMRA closes this gap by clearly covering prospecting in Antarctic offshore areas and thus prohibiting it, as noted above, prior to timely entry into force.

After Entry Into Force

The Section on 'The Resources and the Economics' above indicates that there is no current economic interest in minerals development in Antarctica. This does not mean, however, that there is no interest in finding out just what the minerals potential of Antarctica is. Once prices rise for any minerals identified in sufficient quantity in Antarctica, companies and nations interested in exploiting them will wish to be in a position to evaluate the economic viability and the technical feasibility of doing so. It is therefore likely that upon entry into force of the CRAMRA, there will be prospecting offshore Antarctica and possibly on the continent itself to assess the minerals potential.

Prospecting

The CRAMRA regulates three stages of minerals activities: prospecting, exploration, and development. Prospecting may proceed without explicit authorization by the institutions established by CRAMRA. As an al-

ternative to prohibiting prospecting until authorized, however, the treaty requires that prospecting conform with a series of standards and requirements meant to safeguard the Antarctic environment and other uses in Antarctica from any possible adverse effects of such prospecting. There are special provisions to deal with liability for damages to the Antarctic environment that may result from prospecting. (See 'Stages: Prospecting' section below.)

Exploration and Development

Exploration and development must be specifically assessed and approved by the institutions established by the CRAMRA. Two further requirements must be met before specific proposals to carry out exploration and development may even be considered:

(1) No exploration or development may take place until a Protocol elaborating the details of a system of response action and liability has been concluded and is in force for any party proposing to undertake exploration/development. This Protocol must be adopted by consensus and enter into force in accordance with the same special formula that governs entry into force of the CRAMRA. There is a commitment in the Final Act of the meeting to begin work on the Protocol at an early stage. (See sections on 'Stages: Prospecting' and 'Liability and Response Action'.)

(2) No exploration or development may take place until a series of steps has been completed as set forth in the CRAMRA. The first step is a threshold decision, requiring consensus that in principle the type of minerals exploration/development proposed in a specific geographic area of Antarctica can be carried out in conformity with the objectives and principles laid out in the treaty. In order to judge whether the objectives and principles can be met, the decision-making institutions must identify information needs and establish criteria to interpret them. Second, before any specific proposals to explore for or develop mineral resources can be considered, the decision-making institutions must adopt more detailed guidelines and rules, as well as contract terms and conditions applicable to specific types of minerals activities in identified geographic areas of Antarctica. These must give effect to the objectives and principles set forth in the treaty. There is in addition a specific proviso that inspection must be effectively provided for in an identified area before exploration or development may take place. (See section on 'How Does the Minerals Treaty Work?')

Institutions

The institutions provided for in the CRAMRA are discussed in more detail below. Within six months of the entry into force of the treaty, the first meeting of the plenary decision-making institution established by the treaty -- the Commission -- must be convened. It will take organizational, financial and other decisions necessary for the treaty and the institutions to begin functioning. Subsequent Commission meetings are to be convened, if necessary, in accordance with a regular schedule, as well as pursuant to specific requests and events (Article 19). The Scientific, Technical and Environmental Advisory Committee first meets within six months of the first Commission meeting, and thereafter in accordance with a schedule determined by the Commission, as necessary to perform its functions.

Once there are concrete expressions of interest in carrying out minerals exploration and development, the institutions will begin meeting regularly in order to carry out their specified functions, and Regulatory Committees may be established. Prior to that point, should prospecting activities or any other matter give rise to concern, a request from six Commission members may trigger a special meeting of the Commission.

What were the major accommodations that the negotiations had to achieve?

There were three major accommodations required in the negotiation of the CRAMRA:

(1) *the internal accommodation*: between the seven nations that claim territorial sovereignty in Antarctica and the rest of the world's nations that do not recognize these claims to sovereignty.

(2) *the external accommodation*: the considerations to be granted to the wider international community relative to their interest in knowing about and benefitting from Antarctic mineral resource activities.

(3) the balance between establishing a practical and workable regulatory system for possible minerals development in Antarctica, and ensuring that decisions to permit minerals activities do not undermine other uses of Antarctica nor significantly alter its relatively pristine environment.

The Internal Accommodation

There is a common misunderstanding among many of those who follow Antarctic issues that the 1959 Antarctic Treaty somehow dispensed with the issue of territorial claims in Antarctica. This is not the case. What the Antarctic Treaty does is preserve the legal positions of those states claiming territory in Antarctica, those states maintaining a basis for claim in Antarctica, and those nations that do not recognize territorial claims in Antarctica.* *The result is that whenever a new question arises that must be addressed by the ATCPs, any agreement they reach on how to address it must equally avoid prejudicing either legal position.* Thus:

The 1972 Convention for the Conservation of Antarctic Seals (CCAS) does not invoke the que*claims.

The 1980 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) resorts to a particular legal 'finesse' that avoids prejudice to these legal positions.

The 1988 CRAMRA resorts to an ingenious mix of decision-making rights and responsibilities to protect the differing legal positions.

Any future agreement on, for instance, such matters as the regulation of tourism in Antarctica, or the implementation of a system of protected areas in Antarctica, will equally have to avoid assigning rights and responsibilities to claimant or non-claimant nations that are viewed as prejudicing their legal positions with respect to sovereign rights in Antarctica.

For a specific description of how the minerals treaty responds to claimant/non-claimant concerns, see the 'Commentary' section below.

The External Accommodation

From the moment the ATCPs first considered the need to develop a legal regime governing the possibility of minerals development in Antarctica in 1970, they were well aware of the interest and concern that this endeavour would evoke among a much wider community of nations not historically involved with the Antarctic Treaty. This recognition arose not least as a result of the negotiations over a legal regime to govern mineral resources development in the deep seabed beyond national jurisdiction, then on-going under United Nations auspices. The United Nations had adopted by consensus in 1970 a resolution terming the deep seabed beyond national jurisdiction the common heritage of mankind, and calling for the elaboration of an international mechanism to regulate that development.

The Law of the Sea Negotiations on Deep Seabed Mining

Recommendation XI-1 was adopted in 1981 to set the terms for the Antarctic minerals regime negotiations. (See Appendix.) It states in its preambular language that the ATCPs are "Mindful of the negotiations that are taking place in the Third United Nations Conference on the Law of the Sea" (LOS). In its operative language it also pays heed to the "responsibilities which may be exercised in the area by other international or-

* The seven nations claiming Antarctic territory are Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom. The two nations with a recognized basis for claim are the USSR and the United States. Neither the USSR nor the United States, nor any other nation in the world recognizes the seven claims. To complicate matters further, the claims of Argentina, Chile, and the United Kingdom overlap.

ganizations", meaning, among others, the institutions contemplated in the LOS negotiations to govern deep seabed mining. (It will be recalled that at the time of the adoption of Recommendation XI-1, the LOS deep seabed mining regime had not yet been definitively challenged by the United States.)

The United Nations General Assembly

Following adoption of the LOS Convention in April 1982, the international community did in fact turn its attention to Antarctica. The delay in their expression of interest from the time of adoption of Recommendation XI-1 in July 1981, to the successful effort to have the United Nations General Assembly (UNGA) consider the question of Antarctica in the fall of 1983, can be attributed to two things: that it took some time for the wider international community to learn that the adoption of Recommendation XI-1 had indeed launched the Fourth Special ATCM to negotiate a minerals treaty as of June 1982, and that the US review and subsequent rejection of the LOS treaty during 1981-82 caused a great deal of turmoil that preempted attention to other matters.

Subsequent debates in the UNGA, led by Malaysia and Antigua and Barbuda, brought the Antarctic Treaty System (ATS) under attack for its exclusive decision-making system, the lack of information readily available on activities in Antarctica and the regular meetings of the ATCPs, and the continuing role permitted the *apartheid* regime of South Africa as a participant in ATS meetings. A number of nations advocated that the governance of Antarctica be brought under UN auspices. As this UNGA debate has evolved (See IIED Reports on Antarctica, 1983-1987), nations critical of the ATS have come to acknowledge that the ATS has in fact proven a successful governing system for Antarctica, and that scarcity of information is no longer a problem in most respects. They have remained strongly critical, however, of the lack of international community participation in the on-going minerals negotiations, and of the 'two-tier' decision-making system in Antarctica that requires states to engage in substantial activities in Antarctica in order to attain the right to take part in decisions. (Since 1983, the non-ATCP nations party to the Antarctic treaties have been invited to attend meetings as observers. They are referred to as the Non-Consultative Parties (NCPs).)

In 1986 the UNGA adopted by vote a resolution calling for a moratorium on the minerals negotiations until all members of the international community could participate fully in them. A similar resolution was adopted in 1987. Immediately following the adoption of CRAMRA, on June 8, 1988, 19 nations issued a statement, circulated to all UN member nations, which expresses regret and deep concern that the ATCPs completely disregarded UNGA resolutions calling for a moratorium; disregarded the 1987 resolution's call for the ATCPs to invite the UN Secretary-General to all ATCMs, including the minerals negotiations; and disregarded the resolution's appeal that the ATCPs exclude the *apartheid* regime of South Africa from participating in their meetings. There is no doubt that the UNGA debate on Antarctica during the fall of 1988 will reiterate these criticisms.

For a specific description of how the CRAMRA deals with the external accommodation, see the 'Commentary' section below.

The balance between establishing a practical and workable regulatory system for possible minerals development in Antarctica, and ensuring that decisions to permit minerals activities do not undermine other uses of Antarctica nor significantly alter its relatively pristine environment.

The relatively pristine Antarctic environment provides a laboratory for scientific research unparalleled elsewhere on Earth. It is also integral in ways not yet fully understood to global climate formation and oceanic circulation. Not least, this unique area warrants protection simply for its aesthetic qualities and wilderness value.

A basic consideration in deciding to initiate the negotiations was to prevent the possible expression of concrete interest in Antarctic minerals development from causing conflicts among the countries active in Antarctica. An equally important consideration was protecting the Antarctic environment and dependent and associated ecosystems from unregulated minerals activities. The underlying presumption was that an agreed legal regime was far preferable to a void.

The states engaged in negotiating the minerals treaty had a variety of national interests to protect. In addition to the basic issue of preserving national positions on the territorial status of Antarctica, these included access to potential mineral resources; preservation of the system of cooperation that has prevailed in the An-

tarctic Treaty System and avoiding its becoming 'the scene or object of international discord'; protection of other uses and activities in Antarctica from potential adverse effects brought about by mineral resource activities, including scientific research and the harvesting of marine living resources; and protection of the Antarctic environment and dependent and associated ecosystems for their own sake and in order to avoid adverse effects on states immediately north of the Antarctic circle or on regional and global environmental processes that sustain life on Earth. Some states gave predominant emphasis to one or another of these interests. In most cases, however, each individual nation was forced to balance the full range of these interests, both in determining its own national position in the negotiations and in compromising or trading-off its national interests to reach agreement with other participants in the negotiations.

For further discussion of the environmental concerns in the negotiations, see the 'Commentary' section below.

Description Of The Convention

The Fourth Special Antarctic Treaty Consultative Meeting (ATCM) was authorized by the Antarctic Treaty Consultative Parties (ATCPs) in July 1981, when they approved Recommendation XI-1 at the XI ATCM in Buenos Aires, Argentina. Recommendation XI-1 charges the meeting with elaborating a legal agreement to govern the possibility of minerals development in Antarctica. The negotiations first convened in June 1982 in Wellington, New Zealand. They have been chaired throughout by Christopher Beeby, currently Deputy Secretary, Ministry of Foreign Affairs, New Zealand.

History and Background

At the VI ATCM in Japan in 1970, the first informal discussions took place about possible interest in minerals development in Antarctica and the need to develop an agreed legal regime that would avoid Antarctica becoming the scene or object of international discord. These discussions were triggered in part by the fact that some of the governments involved had received inquiries from marine geophysical companies interested in prospecting in Antarctica, and in part by research results indicating that Antarctica had been part of the Gondwanaland supercontinent. The issue was examined at the VII ATCM in late 1972, and the ATCPs agreed to place the subject of 'Antarctic Resources - Effects of Mineral Exploration' on the agenda of the VIII ATCM in Norway in 1975. Following VII ATCM, two significant events took place that added to possible interest in Antarctic minerals development:

(1) the *Glomar Challenger*, in the course of participating in the Deep Sea Drilling Project (DSDP), discovered traces of methane and ethane in the Ross Sea continental shelf in 1973. These are often associated with the presence of oil resources; and

(2) the OPEC (Organization of Petroleum Exporting Countries) established the oil embargo that resulted in a significant increase in the price of oil.

When the subject of Antarctic minerals was reconsidered at VIII ATCM in 1975, it was decided to convene a special Preparatory Meeting before the IX ATCM in London in 1977. This meeting took place in Paris in June/July 1976. Its results were central to the evolution of the minerals treaty.

Meanwhile, during the mid- to late-nineteen-sixties and into the early seventies there were reports of increased fishing in the ocean around Antarctica. Several states parties to the Antarctic Treaty expressed concern that overfishing might adversely affect depleted and endangered species in the Southern Ocean and wreak substantial damage on the Southern Ocean food chain, so highly dependent on the Antarctic 'krill' or shrimp. Priority was therefore placed on first concluding a treaty on the conservation of marine living resources. At the same time, the conventional wisdom among Antarctic policymakers was that it might be easier to first tackle a resources management regime for living resources, before attempting to take on the more difficult negotiation of a mineral resources regime, whose implications for varying legal positions in Antarctica would be far more fundamental. If they could succeed in concluding a marine living resources treaty, they might then turn to a minerals regime.

The decision to launch the second special ATCM to negotiate a marine living resources treaty was taken at the IX ATCM in London in 1977. The negotiations were concluded in 1980. This paved the way for adoption at the following ATCM in 1981 of Recommendation XI-1, which launched the Fourth Special ATCM on the

minerals regime.

The Seeds of the Convention

The Special Preparatory meeting on minerals, which took place in Paris in 1976, outlined four basic principles that were incorporated into Recommendation IX-1 at the London ATCM in 1977 and subsequently carried over into Recommendation XI-1, to form the basis upon which the minerals regime negotiations were ultimately to proceed. Recommendation XI-1 added a final principle to the original four:

- (i) the Consultative Parties should continue to play an active and responsible role in dealing with the question of Antarctic mineral resources;
- (ii) the Antarctic Treaty must be maintained in its entirety;
- (iii) protection of the unique Antarctic environment and of its dependent ecosystems should be a basic consideration;
- (iv) the Consultative Parties, in dealing with the question of mineral resources in Antarctica, should not prejudice the interests of all mankind in Antarctica;
- (v) the provisions of Article IV of the Antarctic Treaty should not be affected by the regime. It should ensure that the principles embodied in Article IV are safeguarded in application to the area covered by the Antarctic Treaty. (Article IV of the Antarctic Treaty preserves claimant/non-claimant positions on Antarctica.)

Seminal discussions in the evolution of the minerals treaty also took place at the X ATCM in Washington in September 1979 and at the preparatory meeting for it in July 1979. Based on the report of the preparatory meeting, the initial outlines of a regime were considered in a working group established at X ATCM on 'The Questions of Mineral Resource Exploration and Exploitation: Legal and Political Aspects'. The combined results of this working group and another on 'Scientific and Environmental Aspects' (see below) led to Recommendation X-1 on Antarctic Mineral Resources. This recommendation builds on the Recommendation IX-1, by specifying that the minerals regime should include means for assessing environmental impacts, determining whether mineral resource activities would be acceptable, and governing all aspects of those activities if deemed acceptable, including "the establishment, as an important part of the regime, of rules relating to the protection of the Antarctic environment". This language became the cornerstone for additional specifications in Recommendation XI-1 as to what should be dealt with in the regime. (See Appendix, Recommendation XI-1, para. 7(i).)

During these early discussions, the ATCPs expressed continuing concern about the possible environmental effects of minerals activities in Antarctica, and they called for several expert studies of environmental implications (See section on 'Additional Reading' below):

The VIII ATCM request to SCAR led to the establishment of a Group of Specialists, which produced and submitted to IX ATCM "A Preliminary Assessment of the Environmental Impact of Mineral Exploration/Exploitation in Antarctica" (EAMREA), 1977. Their report was considered by a group of experts constituted at IX ATCM and chaired by Martin Holdgate, which completed the 'Holdgate Report' on Mineral Exploration and Exploitation.

In preparation for X ATCM, there was a meeting in June 1979, in Washington, DC which produced the "Report of the Group of Ecological, Technological and Other Related Experts on Mineral Exploration and Exploitation in Antarctica". This was preceded by a workshop sponsored by the Rockefeller Foundation, whose report, "Oil and Other Minerals in the Antarctic: the environmental implications of possible mineral exploration or exploitation in Antarctica", by M.W. Holdgate and Jon Tinker, was published by SCAR in 1979.

Recommendations X-1 and X-7 requested additional information from SCAR, which then constituted a new Group of Specialists on Antarctic Environmental Implications of Possible Mineral Exploration and Exploitation (AEIMEE). This group produced two reports, edited by Robert H. Rutherford and published by SCAR in 1986. The original reports were produced in 1981, for XI ATCM, and in 1983, in preparation for the July 1983 meeting of the minerals negotiations in Bonn, FRG.

How Does the Minerals Treaty Work?

The CRAMRA regulates three stages of minerals development activities: prospecting, exploration, and

development. Each of these stages is defined to include related logistic support. Prospecting may proceed without prior authorization, although it may be regulated retroactively, whereas exploration and development require express approval by the institutions of the regime. Prior to considering specific applications for exploration and development, there must be a decision in principle that such activities, within a limited, defined, geographic area of Antarctica may be acceptable. This decision is called the 'identification of the area'. (See 'Stages' section below.)

It should be recalled that CRAMRA establishes a regulatory framework, not a detailed mining code. It specifies a series of binding legal obligations with which all stages of minerals activities must comply, the basic principles and standards. (These principles are discussed in the final 'Commentary' section below.) Once an area is identified, the institutions then interpret and apply the basic principles and standards. They must identify detailed criteria and regulations to give effect to these principles with respect to every decision taken and measure adopted.

In describing how the CRAMRA works, this section distinguishes the prospecting stage from the exploration/development stage, because the former may be carried out before any specific implementing regulations exist. Thus while the same basic legal obligations - principles - apply to prospecting as to exploration and development, there are some specific requirements and procedures established in the CRAMRA that are only applicable to prospecting.

Area of Application

The CRAMRA regulates the three stages of Antarctic mineral resource activities on the Antarctic continent and all Antarctic islands and their associated ice shelves south of 60 degrees south latitude, as well as in the seabed and subsoil of their adjacent offshore areas. It does not regulate Antarctic mineral resource activities in the deep seabed beyond the geographic extent of the continental shelf. The term 'geographic extent' is to accord with the definition of the continental shelf in international law and to be determined, as specified in the Final Act, by reference to all of the criteria and rules embodied in paragraphs 1 to 7 of Article 76 of the 1982 United Nations Convention on the Law of the Sea.

The CRAMRA therefore covers activities taking place in adjacent offshore areas north of 60 degrees south latitude that extend from Antarctic islands south of 60 degrees. It does not cover, as recorded in the Final Act, activities in any continental shelf appurtenant in accordance with international law to islands situated north of 60 degrees south latitude that may extend south of the 60-degree line. Subject to these stipulations, CRAMRA applies to the Antarctic Treaty area (south of 60 degrees south latitude), except that the application of Convention articles relevant to determining possible impacts outside these areas, including impacts on dependent or associated ecosystems, is in no way limited (Article 5).

The Institutions

CRAMRA establishes five separate institutions: the Commission, the Special Meeting of States Parties, the Scientific, Technical and Environmental Advisory Committee, different Regulatory Committees, and a Secretariat.

The Commission

The Commission will be composed of all Parties that are ATCPs as of November 25, 1988, when the Convention is opened for signature. In addition, any other Party engaged in substantial scientific, technical or environmental research in the treaty area that is directly relevant to the decisions called for in the Convention, and any Party sponsoring minerals exploration or development under a valid Management Scheme during the period of its validity, may become members. For states seeking membership on the basis of their research, if they are already ATCPs, they are deemed to have met the requirements for membership unless more than one-third of the members object. If they are not already ATCPs, a consensus decision is required for them to become Commission members (Article 18).

Observer status in the Commission is open to any Party and to any Party to the Antarctic Treaty that is not a Party to the CRAMRA. The Commission may grant observer status in addition to relevant international organizations, including non-governmental organizations, that might assist it in its work (Articles 18 and 34).

Commission decisions are normally taken by a three-quarters majority vote, except that consensus is required with respect to budgetary and financial matters, with respect to decisions to identify an area for pos-

sible minerals exploration and development, and with respect to measures to elaborate a principle that there shall be no discrimination against any Party or its operators in the implementation of the Convention. Procedural matters are determined by a simple majority vote (Article 22).

The Special Meeting of States Parties

This group is composed of all Parties to the CRAMRA and meets only to provide advice to the Commission whenever it must determine whether to identify an area for possible minerals exploration and development. Its advice must reflect all views expressed and the conclusions reached, but the Special Meeting is not a decision-making body (Articles 28 and 40).

Observer status is open to any Party to the Antarctic Treaty that is not a Party to the CRAMRA, and to any international organizations accorded observer status in either the Commission or the Advisory Committee (Articles 28 and 34).

The Advisory Committee

The Advisory Committee is composed of all Parties to CRAMRA. Its reports are presented to the Commission and to any relevant Regulatory Committee, and must reflect the conclusions reached at any of its meetings and all views expressed (Articles 23 and 27). It is not a decision-making body. (The role of the Advisory Committee is discussed in more detail in the 'Commentary' section below.)

Observer status in the Advisory Committee is open to any Party to either the Antarctic Treaty or the Convention on the Conservation of Antarctic Marine Living Resources that is not a Party to CRAMRA. Observer status for international organizations, including non-governmental organizations, is subject to decisions by the Commission (Articles 23 and 34).

Regulatory Committees

A separate Regulatory Committee is constituted for each specific geographic area identified by the Commission for possible minerals exploration and development. Each Committee is composed of 10 original members, who must be members of the Commission. In addition, if not among the original 10, Parties submitting applications to a particular Committee may be members of that Committee for consideration of the application, and Parties sponsoring approved exploration and development activities within the area of competence of a Committee are members for the duration of these activities. The latter may only take part in decisions affecting their particular contract (Management Scheme). There is also a provision for interim membership by the Party that triggered establishment of the Regulatory Committee with a request for identification of the area. (See 'Stages' section below.) That Party remains a member until an application for an exploration permit is lodged (Article 29).

The criteria according to which Regulatory Committee members are selected are very detailed, because of the role played by the Regulatory Committees in accommodating claimant and non-claimant positions on Antarctica. They are as follows: there are four members that maintain claims in Antarctica, which must include any state(s) with a claim in the area identified, and six that do not assert claims, which must include the United States and the USSR that maintain a basis of claim in Antarctica. The seats not occupied by obligatory members are to be allocated on the basis of a recommendation developed by the Chairman of the Commission, following consultations by him.

The Chairman's recommendation is to take into account three factors: (i) the inclusion of Commission members that have contributed substantial scientific, technical, or environmental information relevant to the decision to identify the area; (ii) adequate and equitable membership of developing nations, having regard to their proportionate representation on the Commission and with a requirement for at least three; and (iii) the principle of rotation of Regulatory Committee membership to further ensure equitable representation of all members of the Commission on Regulatory Committees. An interpretive statement in the Final Act notes that, as Commission membership increases, the requirement for at least three developing nation members, as well as the total of ten members on Committees (by reference to the limit on six non-claimant members) may be amended to take account of changing proportions between developed and developing nation members of the Commission. The three out of ten developing nations provided for reflects the existing proportion of developing nations among the ATCPs, six out of 20. With respect to the selection of non-obligatory claimant members, the Chairman must make his recommendation upon the nomination of the relevant claimants, and with respect to the selection of non-obligatory non-claimants, he must "give full weight" to the views of all non-claimant Commission members. The Convention is not very clear about what happens in the event that the

Commission cannot agree on the Chairman's recommendation. Presumably the Chairman re-engages in consultations, but since the decision lies with the Commission, in the end it may intervene to come up with an alternative (Article 29).

Observer status in a Regulatory Committee is open to any Party to CRAMRA (Article 30). There is no explicit provision for international organization observers, although nothing precludes a Committee decision to provide for such.

Regulatory Committee decisions on substantive matters are normally taken by a two-thirds majority vote, and on procedural matters by a simple majority. Decisions to approve exploration or development proposals, as well as decisions to approve and revise the general requirements applicable to exploration and development, require that the two-thirds majority include a specific majority within both the group of four claimant members and the group of six non-claimant members (Article 32). The Final Act of the meeting agreed that it was desirable that the two-thirds majorities include at least one developing nation. (See 'Stages' section below.)

The Secretariat

The Commission may establish a Secretariat staff as necessary. It would perform functions assigned it in the Convention and entrusted to it by any of the four other institutions, subject to approval of the budget (by the Commission) (Article 33).

Stages: Prospecting

Prospecting, the initial stage of mineral resource activity, is not subject to prior authorization by the institutions, whereas exploration and development are prohibited unless specifically permitted. For this reason it is useful to review applicable provisions separately, although the same standards and principles apply to all mineral resource activities, including prospecting.

Prospecting does not confer on the operator any rights to mineral resources. It does allow the operator to retain data and information of commercial value as long as the sponsoring state certifies that they continue to have commercial value. There is a presumption that basic data and information should be made available no later than 10 years after collected, and the Commission is assigned an oversight function in this regard (Article 37).

Although no express authorization by the institutions of the regime is required for prospecting, all of the Convention's general principles and standards do apply, and it is up to the sponsoring state to ensure compliance by its operators. The accommodation in the negotiations that allowed prospecting to proceed without express authorization has several elements:

Definition: Prospecting by definition excludes any dredging and excavations, except for the purpose of obtaining small-scale samples, as well as drilling into rock and sediment at depths of more than 25 meters (Article 1);

Applicable Principles and Standards/Commission Measures: Prospecting is subject to all of the principles and standards specified in the Convention, as are exploration and development. The Commission may at any time adopt measures relevant to all prospectors, interpreting these principles and standards, to ensure that activities are consistent with the Convention and any measures adopted pursuant to it (Articles 21 and 38). It may also set fees to be submitted with prospecting notifications to cover the administrative costs of handling them (Articles 21 and 37).

Advance Notification and Information Requirements: A state sponsoring prospecting must notify the Commission nine months in advance of planned prospecting, and provide information on where, for what type(s) of mineral resource(s), with what methods, and in accordance with what work program of what duration the prospecting will take place. It must also provide information on, and certify that, the operator has a substantial and genuine link with it and is financially and technically qualified to carry out the proposed prospecting in a manner consistent with the Convention (Article 37).

Environmental Impact Assessment, Monitoring and Contingency Plans: The sponsoring state must also provide with this notification an assessment of environmental and other possible impacts, describe measures and monitoring programs to be adopted to avoid harmful environmental consequences or undue interference with other established uses of Antarctica, and outline emergency response measures, including

evacuation plans (Article 37).

Safeguards: The Commission must circulate prospecting notifications without delay to all Parties and observers attending Commission meetings (Article 37). Any state member of the Commission may request clarifications from a sponsoring state if it considers that the information supplied in the notification, or on-going prospecting activity, may be inconsistent with the Convention or measures in effect pursuant to it. If that state remains unsatisfied, and if five other states support its call for a meeting of the Commission, such a meeting shall be convened to consider the issues and take appropriate action. Any measures subsequently adopted by the Commission must, within time limits prescribed by the Commission, be applied by all relevant sponsoring states to their operators, and these states must notify the Commission that they have done so (Article 38). Any six members of the Commission may also convene a meeting of the Advisory Committee if they deem it necessary (Article 24).

There is also provision for an expedited determination by the Arbitral Tribunal (constituted in accordance with the Annex to the Convention), at the request of any party to a dispute, on the need for emergency provisional measures either to preserve the respective rights of the parties to the dispute, or to prevent serious harm to the Antarctic environment or dependent or associated ecosystems (Article 6, Annex). Disputes over prospecting are subject to this procedure. (See section on 'Dispute Settlement/Review' below.)

Removal and Site Rehabilitation: Operators, when they terminate prospecting activities, must ensure the removal of all installations and equipment and site rehabilitation (Article 37).

Annual Reports and Updates: States sponsoring prospecting are obliged to provide annual reports to the Commission and notification of any changes in the information originally supplied, as well as notification of when prospecting has been terminated, including removal of equipment and site rehabilitation (Article 37).

Inspection: Inspection of Antarctic mineral resource activities, including prospecting, may be carried out both under the Antarctic Treaty, to ensure that they are not inconsistent with the purposes of that treaty, and pursuant to an inspection system established by the CRAMRA. (See section on 'Compliance/Enforcement' below.) Referencing the Antarctic Treaty inspection provisions in the CRAMRA facilitates their use in relation to prospecting, which may occur before the CRAMRA inspection system is fully in place. Inspections may cover offshore installations and equipment, as well as ships at points of discharging or embarking cargoes or personnel (Articles 11 and 12).

Liability and Response Action: The liability Protocol referred to above may not have been completed by the time initial prospecting takes place. Bearing this in mind, the CRAMRA requires sponsoring states to ensure that their prospectors maintain financial and technical means to take timely response actions if their activities result in or threaten to result in damage to the Antarctic environment or dependent or associated ecosystems. (Response actions are defined to include prevention, containment, cleanup and removal - Article 8(1).) If its operator fails to complete such response action, the sponsoring state is responsible for doing so (Article 37).

In relation to liability, the operator is strictly liable (no-fault) for damages defined in the Convention. During the period before the Protocol is in force, the question of limits to liability for prospecting is not resolved, since any applicable limits determined in the Protocol will not apply. These will be subject to litigation in national courts (see below). The sponsoring state, however, is responsible for determining the financial capacity a prospector it sponsors must maintain, commensurate with the nature and level of the activity and the risks involved, in order to be able to fulfill potential liabilities as outlined in the Convention. During the negotiations, it was not possible to reach agreement that the sponsoring state would actually shoulder any outstanding liability incurred by operators it sponsors. The sponsoring state is, however, liable for damages caused by its failure to carry out its obligations under the Convention -- obligations such as ensuring the financial and technical capabilities of its operators (Articles 37 and 8). (See section on 'Liability and Response Action' below.)

Finally, the CRAMRA provides that during the period before the Protocol enters into force, each Party to the treaty must ensure that recourse is available in its national courts for adjudicating liability claims against prospectors, and specifically for adjudicating claims against prospectors that it has sponsored. More uniquely, the Convention requires that each Party ensure that the Commission has standing to pursue in its national courts relevant liability claims in respect of environmental damage (Article 8). These requirements carry the qualifying statement that the Party is obliged to do so only "in accordance with its legal system", but in an un-

derstanding accepted by the final meeting, it was made clear that a defense based on sovereign immunity is precluded (Article 8). The Final Act reinforces this point by noting that an operator undertaking prospecting is defined to include states parties. The Final Act of the meeting also records the agreement that multiple judgments are not permitted in respect of the same liability claim; that is, that when a claim is being adjudicated in one nation's courts or after a final judgment has been rendered, it may not be subject to any additional adjudication.

Stages: Exploration and Development

An expression of interest in exploration and development is the trigger for a series of evaluations and actions that may ultimately result in approval of a specific contract to carry out minerals exploration and, possibly, subsequent development activities. The 'contract' is referred to as a Management Scheme in the CRAMRA and, when approved, results immediately in the issuance of an Exploration Permit conveying exclusive rights to an operator to explore, and, subject to subsequent re-examination and possible modification to the Management Scheme, to develop specific mineral resources. These activities must be carried out in accordance with the terms and conditions specified in the Management Scheme.

Notification of Request to 'Identify an Area': Any state party to CRAMRA may request that a specific area of Antarctica be made available for exploration and development activities. The notification submitting this request must contain information on the area and the resource(s) of interest, the likely scale of activities involved and the methods that could be used, and a detailed assessment of the environmental and other possible impacts of the activities, including those on other established uses of Antarctica. Such a notification is circulated to all Parties and observers attending Commission meetings, and within two months the Commission must be convened to consider it (Article 39). The Commission may set fees to accompany the notification, in order to cover the administrative costs of handling it (Articles 21 and 39).

Review Procedures: The next step is for the Advisory Committee to review the notification and provide a report to both the Special Meeting of States Parties and the Commission. Then the Special Meeting meets to consider whether the request and supporting information would be consistent with the Convention and reports on this to the Commission (Article 40).

Decision by the Commission: Taking into account the reports of the Advisory Committee and the Special Meeting of States Parties, the Commission decides whether to identify the area as requested. This decision is taken by consensus among Commission members. If the Chairman of the Commission believes that consensus will not be achieved, he shall consult with Commission members, and, if necessary, convene the most directly interested members to try to reconcile differences and produce a generally acceptable proposal (Article 22).

The Commission's decision is only with respect to the mineral(s) and the area specified in the request. The Commission does have some leeway to amend the area so that it forms a coherent unit for the purposes of resources management (Articles 40 and 41). There are also provisions for the Commission, pursuant to another request for identification, to incorporate within an already identified area additional mineral resource(s) and/or geographic areas (Article 42).

Restrictions/Protected Areas: In taking its decision, the Commission may exclude part of the area requested from that available for exploration and development activities, or it may restrict or prohibit such activities to give effect to protected area designations as provided for in the Convention. Areas already designated as Specially Protected Areas or Sites of Special Scientific Interest under the Antarctic Treaty are off limits (Articles 41 and 13). (See final 'Commentary' section below.)

Implementing Rules and Regulations by the Commission: The Commission may at any time adopt (by its normal 3/4 majority) measures of general applicability to exploration and development activities (Articles 41 and 21). In taking its consensus decision to identify an area, the Commission must prescribe any additional conditions required to ensure that the area identified is in conformity with the Convention, and it may prescribe general guidelines that relate to operational aspects of minerals activities. There are in addition two specific requirements that the Commission must implement in its decision to identify an area:

(1) Dispute Settlement Options vis-a-vis Regulatory Committees for Private Operators/States: It must establish procedures for third-party dispute settlement with respect to future Management Schemes, specifically when it is alleged that a Regulatory Committee has violated the Convention in declining a Management Scheme, declining to issue a development permit, or deciding to suspend, modify or cancel a Management

Scheme or to impose monetary penalties. These procedures will expand on the third-party settlement options for state-to-state disputes set forth in the Convention (see section on 'Dispute Settlement/Review' below), by permitting both private operators and an institution established by the CRAMRA to be party to a dispute. They must permit both states and operators to initiate proceedings against a Regulatory Committee. Before resorting to these procedures, however, the issue under dispute must first be referred back to the relevant Regulatory Committee for consideration (Articles 41 and 59).

(2) **International Participation:** The Commission must give effect to the principles contained in Article 6 of the treaty: to promote cooperation and encourage international participation in minerals activities among all Parties to the CRAMRA, with special emphasis on ATCPs and developing nations. This is to be accomplished by elaborating opportunities for participation in joint ventures or other alternatives up to a defined level -- such as a percentage investment in the venture. The Commission must also determine the procedures according to which such participation will be offered. The Convention makes clear that any such arrangements are to be realized directly through Parties and their operators. In addition, there is an interpretive statement in the Final Act that indicates that these provisions do not prejudice the right of any applicant/operator, in offering participation in any proposed activity consistently with these articles and measures adopted, to exercise freedom of choice over partners in a joint ventures, including the terms of their partnership. Every application for exploration or development must contain a description of how it complies with these measures (Articles 41, 6, 44 and 53).

Finally, there is a requirement that the Commission, before any applications are lodged with the Regulatory Committee (see below), must adopt general measures (*by its normal 3/4 majority*) relating to Regulatory Committee action to suspend, modify or cancel Management Schemes, or to impose monetary penalties on operators. These measures may address the consequences of such actions, including possible mitigation (e.g., compensation) for operators (Article 51). (See section on 'Compliance/Enforcement' below.)

Implementing Rules and Regulations by the Regulatory Committee: Immediately following the decision by the Commission to identify an area, the relevant Regulatory Committee is to be constituted. It must divide its area of competence into blocks for which applications to conduct minerals exploration and development may be entertained; establish application fees and procedures for handling applications; and establish periods within which applications received are to be considered as simultaneous. As a result, it must also determine a method to resolve competing applications, for which there are additional specifications in the Convention (Articles 43 and 45).

The Regulatory Committee must also draft general requirements for exploration and development within its area of competence that address the terms and conditions that constitute a Management Scheme (operator's contract). These requirements must give effect to the implementing rules and regulations prepared by the Commission, noted above. The block sizes and fees adopted by the Committee are subject to any relevant measures the Commission may have adopted (Articles 43 and 47). *These general requirements must be adopted by a two-thirds majority of the members of the Committee (seven out of ten), which majority must include at least half of the four claimant state members and at least half of the six non-claimant state members.*

Safeguards: Once the Regulatory Committee completes the implementing rules and regulations for which it is responsible, these are made available to all members of the Commission. It must also make them publicly available, along with all relevant implementing rules and regulations adopted by the Commission. Six members of the Commission may at any time request a special meeting of the Commission; for example, in the event that they did not find these regulations in accordance with the provisions of the Convention or relevant Commission measures (Article 19). The role of the Commission in this respect is to seek to ensure consistent application of the standards and principles in the Convention as well as their effective application. The views of the Advisory Committee are to be taken fully into account by the Regulatory Committee in drafting relevant regulations (Article 43), and any six members of the Commission may convene a meeting of the Advisory Committee if they deem it necessary (Article 24).

Application for an Exploration Permit: Once the Regulatory Committee has completed the implementing regulations, applications may be submitted by any Party for an operator it sponsors. These must contain detailed information on the operator, a detailed description of the proposed exploration activities, and a description in as much detail as possible at that time of later development activities. The information must identify the mineral(s) and the block applied for, provide a detailed explanation of how the proposed activities conform with the general requirements specified by the Regulatory Committee; include a detailed assess-

ment of environmental and other possible impacts, including those on other established uses of Antarctica; and describe the operator's ability to respond effectively to accidents. It must also indicate how the application complies with the measures on international participation adopted by the Commission (Article 44).

The sponsoring state must certify that the operator has the capacity to comply with the general requirements specified by the Regulatory Committee, that the operator is technically competent and financially capable, and that the operator has a substantial and genuine link with it (Article 44).

Examination of the Application: The next stage is to fashion the application into a 'contract' or Management Scheme, prescribing specific terms and conditions governing the operation. The Advisory Committee is consulted on how to revise or adapt the proposed activities to conform with the Convention and all relevant implementing measures (Article 45). In carrying out its examination and preparing the Management Scheme, the Regulatory Committee must rely in particular on the sponsoring state, any state(s) with claims within the area of competence of the Regulatory Committee, and possibly one or two additional members (Article 46).

Decision by the Regulatory Committee: The Regulatory Committee may decline an application at any time during its consideration if it does not believe that the proposed activities can be adapted to conform to Convention requirements (Article 45). *In order to be approved, the Management Scheme must receive a two-thirds majority (7 out of 10) of the members of the Regulatory Committee, which majority must include a simple majority of the four claimant states on the Committee, and a simple majority of the six non-claimant states on the Committee. The sponsoring state vote does not count toward these majorities.* This approval results in issuance of an Exploration Permit granting exclusive rights to the operator to explore, and, subject to the steps noted below, to develop the mineral resource(s) identified in the Management Scheme in accordance with its terms and conditions (Articles 45, 48 and 32).

Safeguards: Within one month of a decision by the Regulatory Committee to approve a Management Scheme, a meeting of the Commission shall be convened if either (1) one member of the Regulatory Committee, or (2) a Commission member that is not a member of the Committee if that member is supported by five other Commission members, so requests. That meeting shall review the approval for consistency with the Commission's earlier decision to identify the area and all relevant implementing measures. The Commission *(by its normal 3/4 majority)* may request that the Regulatory Committee reconsider its decision (Article 49).

There are provisions for the Regulatory Committee *(by its normal 2/3 majority)* to suspend, modify, or cancel a Management Scheme or to impose monetary penalties as follows: unacceptable impact or threat thereof on the Antarctic environment or dependent or associated ecosystems (suspend, modify, or cancel); failure to comply with the Convention, measures in effect pursuant to it, or the applicable Management Scheme (suspend, modify, cancel, penalties); or termination of a genuine link between the operator and the sponsoring state (cancel). Cancellation alone entails cancellation as well of the Permit, and thus loss of the operator's exclusive rights. The Advisory Committee's views will be sought in relation to issues of an environmental nature. The Convention also provides that the Commission *(by its normal 3/4 majority)*, prior to any applications being lodged with the Regulatory Committee, must adopt general measures relating to these Regulatory Committee actions and the consequences thereof. These measures are to address the environmental impact situation and the failure to comply situation, and they may include mitigation (e.g., compensation) for operators (Article 51).

In addition, as noted in the section above, the Commission in its consensus decision to identify an area must develop judicial review procedures to deal with Regulatory Committee decisions to decline a Management Scheme, to decline to issue a development permit, or to suspend, modify or cancel a Management Scheme or impose monetary penalties (Article 59).

Finally, there is provision for an expedited determination by the Arbitral Tribunal at the request of any party to a dispute on the need for emergency provisional measures either to preserve the respective rights of the parties to the dispute, or to prevent serious harm to the Antarctic environment or dependent or associated ecosystems (Article 6, Annex). (See section on 'Dispute Settlement/Review' below.)

Application for a Development Permit: The sponsoring state may lodge an application for a development permit on behalf of its operator if that operator holds a valid exploration permit. The information contained in the application must update all the information provided when the application was presented for the Exploration Permit, as well as recertification by the sponsoring state of operator capabilities and its substan-

tial and genuine link. This information must include a detailed assessment of the environmental and other impacts of the proposed activities. In addition, the application must identify any modifications proposed to the Management Scheme and any additional measures to be taken to bring the proposed development activities into conformity with the Convention and relevant implementing measures in effect at that time (Article 53).

Examination of the Application: Drawing in particular on the sponsoring and claimant state members of the Regulatory Committee as noted above, the Regulatory Committee will examine in particular any modifications to the development activities envisaged at the time of the application for an Exploration Permit, and consider whether development activities would cause previously unforeseen impacts on the Antarctic environment or dependent or associated ecosystems. The Advisory Committee is fully consulted on how to modify the proposed activities to conform with the Convention and all relevant measures (Articles 46 and 54).

Decision by the Regulatory Committee: Two-thirds of the members of the Regulatory Committee (7 out of 10), including a simple majority of its four claimant state members and a simple majority of its six non-claimant state members, must either (1) agree on modifications to the Management Scheme to ensure that the activities are undertaken consistently with the Convention and its implementing measures, or (2) agree that modifications are not necessary. If a situation arises where the Regulatory Committee cannot agree on proposals for modifications to the Management Scheme, nor agree that they are not necessary, it will presumably have to revise its proposals for modifications until they can be agreed upon. Once a decision is reached, the Regulatory Committee is to issue a Development Permit to the operator (Articles 54 and 32).

Safeguards: The same safeguards noted above with respect to the Exploration Permit apply with respect to the Development Permit.

Liability and Response Action

The negotiations over the treaty's provisions on response action and liability for damages to the Antarctic environment and dependent and associated ecosystems were very difficult and time-consuming (Articles 8 and 37). In the end it was decided that in lieu of addressing these matters in great detail in the treaty itself, there would be a subsequent negotiation to conclude a Protocol on liability. The Final Act of the meeting records a commitment to begin work on the Protocol at an early stage. As noted above, while the general provisions in the treaty on liability apply to all stages of minerals activity, as will the Protocol, there are added elements that apply specifically to prospecting prior to entry into force of the Protocol. (See section on 'Stages: Prospecting' above.) Specific requirements relating to liability and response action for exploration and development will be covered by the terms and conditions of a Management Scheme.

Response Action: The Convention establishes an outright obligation on the part of any operator conducting any stage of minerals activities to undertake "necessary and timely" response action, if the activity results or threatens to result in damage to the Antarctic environment or dependent or associated ecosystems. Response action is defined to include prevention, containment, removal and cleanup. The operator is also liable for payment of reasonable costs of necessary response actions taken by others (Article 8).

Operator Liability: The operator is strictly liable (no fault) for any damage to the Antarctic environment or to dependent or associated ecosystems, including payment in the event that these have not been restored to the *status quo ante*; loss of or impairment to an established use of Antarctica or of dependent or associated ecosystems arising out of environmental damage; loss of or damage to property of a third party or loss of life or personal injury of a third party, arising directly out of environmental damage; and reimbursement of reasonable costs of actions taken by others to restore the *status quo ante* (Article 8).

The operator may be liable for loss of life, personal injury or loss of or damage to property not covered by the Convention under other applicable law (e.g., other national or international law).

State Liability: During the negotiations, it was not possible to reach agreement that the sponsoring state would actually shoulder any outstanding liability incurred by operators it sponsors. The sponsoring state is, however, liable for damages caused by its failure to carry out its obligations under the Convention - obligations such as ensuring the financial and technical capabilities of its operators and their compliance with the Convention. This liability is limited to that not otherwise satisfied (Article 8).

The sponsoring state may also be liable for any types of liability not specifically assigned to the operator by the Convention under other applicable rules of international law, if it has failed to carry out its obligations

with respect to its operator under the Convention (Article 8).

Restrictions on Liability: The Convention allows for two defenses by the operator, for which the burden of proof rests with the operator: damage caused directly by, or the extent to which it was caused directly by (1) an exceptional natural disaster in the already exceptional natural conditions of Antarctica, which could not reasonably have been foreseen; and (2) armed conflict or an act of terrorism against the operator, against which no reasonable precautionary measures could have been effective (Article 8).

In addition, if the operator proves that the damage has been caused totally or in part by an intentional or grossly negligent act or omission of the party seeking redress, the operator may be relieved totally or in part from its obligation to pay compensation for that damage (Article 8).

What is Damage?: Damage has been defined to mean any impact on the living or non-living components of the Antarctic environment or dependent or associated ecosystems, including harm to atmospheric, marine or terrestrial life, beyond that which is negligible or which has been assessed and judged to be acceptable pursuant to the Convention (Article 1). Some have expressed concern that this means that once exploration or development activities have been approved, they can never be determined to result in liability. This is not the case. Two situations may arise:

(1) An activity may have been approved, it having been determined that the operator's plans would not result in unacceptable impacts judged in accordance with the Convention's standards and implementing regulations. This judgment turns out to be wrong, and monitoring may reveal that the impacts are more serious than originally thought. In this case, the operator is not liable for any damage caused. His operation, however, could be suspended, modified, or cancelled to avoid further impacts, and the original judgment would undoubtedly be corrected in subsequent assessments. In addition, the Protocol could address how to respond to and remedy such damages. (This eventuality is not explicitly referred to in the situations the Protocol must address.)

(2) An activity may have been approved, after having assessed as very low the risk of a particular event/accident that could result in unacceptable damage. Nevertheless, the unlikely event does occur and damage results. In this case, the impacts were assessed as unacceptable in the first instance, and the operator would be liable for damage.

The Liability Protocol: As noted earlier, no state may submit an application for exploration or development until the Protocol has entered into force for it. The Protocol must be adopted by consensus among Commission members and will enter into force in accordance with the provisions for entry into force of the Convention itself. The Protocol's provisions may deal with appropriate limits on liability, and they must prescribe mechanisms to assess and adjudicate liability claims and to ensure that means are provided (1) to assist with immediate response action and (2) to satisfy unmet liability. Unless the negotiators agree on other means for doing so, the Protocol shall establish a fund or funds to meet these objectives. The Convention notes that unmet liability may result from the operator being financially incapable of meeting its obligations in full, from limits established on operator liability, from successful defenses against liability, or from damages of undetermined origin (Article 8).

One of the very contentious subjects in the negotiations was whether to allow for any defenses or limits on liability for damage to the environment. The trade-off was that limits may be addressed in the Protocol (and the fund or other means would apply once those limits are reached), and that two defenses, relatively narrowly construed, are permitted. The Protocol is not directed to address a possible review of these defenses, as had been proposed. It will presumably have to interpret them.

Compliance/Enforcement and Dispute Settlement/Review

Enforcement issues are difficult to agree on in the Antarctic context, because they relate so directly to the rights of a sovereign state in its territory. Both claimants and non-claimants wish to avoid any provisions in the Convention that prejudice their position on sovereignty in Antarctica. The result is a balance between requirements for enforcement and compliance that do not specifically assign enforcement rights, coupled with universal rights for all Parties to ensure compliance and carry out inspections, institutional rights to carry out inspections and monitoring, and reporting requirements by sponsoring states and/or operators. These are supplemented by 'sunshine' provisions that are relatively forthcoming for an international agreement, including requirements for observer participation, advance public notice and comment, and an extensive public

record.

Compliance and Enforcement are also promoted by the safeguards identified in the 'Stages' section above. These are (1) the ability of states to call for a reconsideration of proposed or on-going prospecting (Article 38); (2) provisions on suspension, modification, cancellation of a Management Scheme and/or monetary penalties in relation to violations of the Convention (Article 51); and (3) provisions that allow Commission or judicial review of decisions (Articles 49 and 59). They also include the possibility that six Commission members may at any time convene a meeting of either the Commission or the Advisory Committee (Articles 19 and 24). Finally, the sanction of liability for damages acts as a deterrent to operators taking risks, and as an impetus to states to carry out their obligations to ensure compliance by their operators to avoid otherwise actionable liability claims.

The specifics of compliance/enforcement and dispute settlement with respect to the exploration and development stages are addressed in the terms and conditions of a Management Scheme. The terms cover inspection, monitoring, reporting requirements, liability and financial guarantees and insurance, enforcement, suspension/modification/cancellation/monetary penalties, dispute settlement, and provisions to avoid and to resolve conflicts with other legitimate uses of Antarctica.

Compliance/Enforcement

In general, no Antarctic mineral resource activities may be conducted except in accordance with the Convention and measures in effect (Article 3). Every Party is obliged to "take appropriate measures within its competence to ensure compliance" with the Convention and measures in effect. A sponsoring state may interpret this to mean responsibility for enforcement over nationals, while a claimant state may interpret it to mean competence to enforce measures within its territory. Every Party must also take appropriate efforts to avoid that anyone engages in any mineral activity contrary to the objectives and principles of the Convention, and draw to the attention of the Commission any activity that may affect the implementation of those objectives (Article 7).

A Party must report to all Parties on any measures taken to ensure compliance. The Commission must inform all Parties of any activity affecting implementation of the objectives or compliance by any Party with its obligations, as well as draw the attention of any non-Party to an activity for which that state is responsible that affects the implementation of Convention objectives (Article 7).

Inspection: Inspection of Antarctic mineral resource activities may be carried out under the Antarctic Treaty (for purposes of that Treaty), and pursuant to a system of inspection established by the CRAMRA. Both Commission members and the Commission or relevant Regulatory Committee may designate inspectors (observers), and aerial inspection may be carried out at any time. **Inspection reports** are to be conveyed to the Commission and to the relevant Regulatory Committee. These reports are maintained as part of the public record (Articles 11, 12 and 21).

Monitoring: Each Regulatory Committee is responsible for monitoring operator compliance with Management Schemes within its area of competence. **Monitoring reports** go to the Commission and to the Advisory Committee (if relevant), and they are maintained as part of the public record. The Commission retains overall responsibility to keep under review the conduct of all minerals activities to safeguard the Antarctic environment (Articles 52 and 21).

Reporting Requirements: There is a specific requirement in the Convention for an annual report on prospecting from the sponsoring state, to be forwarded to the Commission (Article 37). Reporting requirements for exploration and development are to be addressed in the Management Scheme, but there is no specific reference to operator/sponsoring state reports and whether or not they are available to the Commission and the public (Article 47).

Sunshine: Observers: The section on institutions above indicates that international organization observers may take part in Commission and Advisory Committee meetings. They are not expressly permitted in Regulatory Committee meetings. Because the Commission receives inspection and monitoring reports and those on prospecting, and the Advisory Committee receives those on monitoring of environmental parameters, these will be available to observers participating in these meetings and they may review them. One gap is that incidents that potentially affect the implementation of the Convention brought to the attention of all Parties (pursuant to Article 7) are not automatically circulated more widely to observer organizations. A second is that any discussion of reporting and compliance that takes place in Regulatory Committees will not

be open to observer organizations. A third is the possibility that operator/state reports on exploration/development will not be made available to the Commission and thus to observers.

The **public record** of the Commission is quite good. It must maintain a public record of its meetings and decisions, and of information, notifications (which includes prospecting notifications and updates, notifications of requests to identify an area, and all the information contained therein), and reports submitted to it (which includes reports of the Advisory Committee and the Special Meeting of States Parties, inspection and monitoring reports, and reports on prospecting). The Regulatory Committee must maintain a public record of its decisions and of Management Schemes in force, and it must publish the implementing rules it has adopted together with relevant Commission measures. However, there is no provision for a record of Regulatory Committee meetings, nor for a report to be transmitted to the Commission.

Advance Public Notice: The Commission is charged with giving advance public notice of matters upon which it is requesting the advice of the Advisory Committee. The Advisory Committee itself is to give advance public notice of its meetings and of matters to be considered at each meeting, so that views on such matters from international organizations interested in them may be received and considered. The Advisory Committee may establish procedures for transmission of relevant information to these organization, which are subject to Commission review (Articles 21 and 25).

Dispute Settlement/Review: State-to-State

The Convention provides two options for binding, third-party settlement of state-to-state disputes over the interpretation or application of the Convention: the International Court of Justice, and an Arbitral Tribunal constituted in accordance with the annex to the Convention. Nevertheless, a state may exempt a category or categories of disputes from these binding procedures unless it decides otherwise in a given instance. On the other hand, there is a list of specific categories of disputes that may not be exempted from the binding procedures. This list of non-exceptionable items in fact covers a large share of the potential disputes that may arise. It covers the interpretation or application of:

- any provision of the Convention or any measure in effect relating to the protection of the Antarctic environment or dependent or associated ecosystems;
- the article on measures taken by Parties within their competence to ensure compliance with the Convention (Article 7(1));
- the article on liability and response action (Article 8);
- the article on prospecting (Article 37);
- the article on inspection (Article 12);
- the articles on protected areas and respect for other uses of Antarctica (discussed below) (Articles 13 and 15); and
- the article on non-discrimination against any Party or its operators in the implementation of the Convention (Article 14).

As with most treaties, there is provision that before proceeding to third-party dispute settlement, the parties to the dispute shall consult together and attempt to settle the dispute by any mutually-agreed means. If the dispute falls into a non-exceptionable category, or if neither state has exempted it, and if it has not been resolved within 12 months, any party may request that the dispute be referred to the binding options. (When states have selected different third-party procedures, the Arbitral Tribunal is the default option.) If the dispute relates to an implementing measure produced under the Convention or to a Management Scheme, any party to the dispute may request after six months that the dispute be referred to the institution that adopted the measure in question. If by the end of 12 months, it has still not been resolved, any party may request that the dispute go to a binding procedure, but in this case the Arbitral Tribunal is the only option.

Expedited Procedure for Provisional Measures: With respect to any of the categories of disputes identified above that may not be excluded from the binding settlement procedures, at any time any Party to such a dispute may request that the Arbitral Tribunal be constituted as a matter of exceptional urgency to indicate or prescribe emergency provisional measures either to preserve the respective rights of the parties to the dispute, or to prevent serious harm to the Antarctic environment or dependent or associated ecosystems. The decision on provisional measures is to be rendered within two months of the appointment of the chairman of the tribunal, which can be no later than 42 days following the initial request. Upon completion of this procedure, settlement of the dispute itself proceeds as otherwise provided for in the Convention (Article 6,

Annex).

Review: There are two review procedures expressly provided for in the Convention: the Commission with respect to a decision to approve a Management Scheme (Article 49), and dispute settlement procedures to be elaborated by the Commission upon identification of an area in respect of Regulatory Committee decisions to decline a Management Scheme, to decline to issue a Development Permit, or to suspend, modify, cancel, or impose penalties with respect to a violation of the Management Scheme (Article 59). These have been noted in the 'Safeguards' sections above. There is also the general review function of the Commission and the ability of any six Commission members to convene a meeting of the Commission or the Advisory Committee.

Dispute Settlement: Operator/Institutions

The judicial review procedures provided for in Article 59 will permit both operators and the Regulatory Committee as an institution to be parties to a dispute. It is to be hoped that the Commission in elaborating these procedures for each identified area will ensure consistency among them.

Limitations

It is difficult to predict the limitations of this system for ensuring compliance with the Convention, since it has not yet been implemented. Nevertheless, due to the sensitivity of claimants and non-claimants to the question of sovereignty in Antarctica, there are potential limitations on the effectiveness of the provisions described in this section. The article on Commission review (Article 49) specifies that the Commission may not assume the functions of the Regulatory Committee, nor substitute its discretion for that of the Committee. The articles on procedures for state-to-state dispute settlement (Article 57), and on the additional procedures for judicial review of Regulatory Committee actions (Article 59), carry the limitation that they are not competent to rule on matters relating to the validity of territorial claims in Antarctica or non-recognition thereof. In addition, they are not to address the exercise by an institution of its discretionary powers in accordance with the Convention, nor to substitute their discretion for that of an institution. These limitations could be interpreted very broadly. On the other hand, the totality of all of the provisions described in this section may in the end prove quite effective.

The Financial Provisions of the CRAMRA

Who gets the revenues from minerals activities was an important element in the debate between claimants and non-claimants in the negotiations. All of the financial decisions noted below, with the exception of operator payments in the nature of taxes or royalties or in kind, require consensus agreement in the Commission (Article 32).

Application/Notification Fees: The Commission may set fees to cover the handling costs of notifications for prospecting and identification of an area. It may also enact measures relating to application fees for exploration or development permits, but the Regulatory Committee is responsible for actually setting the application fees, subject to any relevant Commission measures (Articles 21, 35 and 43).

Operator Payments: There are two additional types of operator payments that will be set out in the terms and conditions of a Management Scheme: payments to support the institutions of the regime, or levies, and payments in the nature of taxes or royalties, or in kind. The first require the Commission to adopt measures, although the Regulatory Committee is to specify them as a term of the Management Scheme. The second is determined by the Regulatory Committee, and they may be required to be paid to the institutions established by the Convention (Article 21, 35 and 47). The financial obligations in the Management Scheme may not be altered without the consent of the sponsoring state unless the Management Scheme specifically provides for their alteration (Article 54). The Final Act of the meeting notes the importance of giving operators reasonable advance notice of the possible extent of their financial obligations before applications may be submitted.

The Budget: The budget is funded by fees, levies, and such other operator payments as may be required to be paid to the institutions. Any shortfall will be met by equal contributions from all Commission members until the Commission, as soon as it is able, adopts an alternative equitable sharing method for these costs. Defaulting members may not take part in decisions. In determining the alternative method, the Commission shall consider the extent to which other Parties (non-Commission members) and observers may contribute to the costs of the institutions. The budget is to cover not only the costs of the institutions, but also the

progressive reimbursement of any state contributions (Article 35).

Disposition of Surplus Revenues: When revenues exceed the budgetary requirements of the institutions (which include the progressive reimbursement of state party expenditures required to make up any shortfalls), the Commission is to determine how to allocate the surplus. It must use these funds:

(1) to promote scientific research in Antarctica, particularly that related to the Antarctic environment and Antarctic resources, as well as widespread participation in that research by Parties (especially developing nation Parties), and

(2) "to ensure that the interests of the members of Regulatory Committees having the most direct interest in the matter in relation to the areas in question are respected in any disposition of that surplus" (Articles 21 and 35). This latter provision may be used by relevant claimant states to seek a special share of the surplus revenues. As noted above, these allocation decisions are subject to a consensus in the Commission.

Subsidies/Unfair Economic Practices

Concerns about possible subsidization of Antarctic minerals activities and resultant adverse impacts on nations producing these minerals domestically resulted in a statement in the Final Act of the meeting to the effect that this issue should be addressed in the context of relevant multilateral agreements (e.g., General Agreement on Trade and Tariffs (GATT)). The CRAMRA Parties that also are Parties to these agreements are to determine conditions of application of these agreements to Antarctic mineral resource activities.

Reservations, Amendment and Withdrawal

Reservations

No reservations to the Convention are permitted, although states may make declarations and statements when they approve the Convention that do not modify the application of the Convention to that state (Article 63).

Amendments

No amendments may be made until ten years after the entry into force of the Convention. Subsequent amendments proposed by any Party must be circulated to all Parties and may be considered at a meeting approved by at least one-third of the Parties. Adoption requires a two-thirds majority, including all Commission members. In two cases -- amendments relating to the Special Meeting of States Parties and amendments related to the Advisory Committee -- a three-quarters majority is required, which must include all Commission members. Entry into force of amendments requires ratification by all Commission members, after which they enter into force for all states that have ratified them. Amendments that enter into force following approval of a Management Scheme may not prejudice that Scheme (Article 64).

Withdrawal

A Party may withdraw two years after submitting a notice of its intent to do so. Since CRAMRA Parties must be Parties to the Antarctic Treaty, any CRAMRA Party that ceases to be a Party to that treaty is deemed to have withdrawn from CRAMRA when it ceases to be a Party to the Antarctic Treaty. If a CRAMRA Party has not approved an amendment within two years of its entry into force, it shall be deemed to have withdrawn from CRAMRA after two more years have passed.

When withdrawal occurs, any rights and obligations of operators sponsored by the withdrawing state cease, *except that* the sponsoring state must ensure that the operator has complied with all of its obligations by the effective date of its withdrawal. Nor do the Party's financial or other obligations pending as of the date of its withdrawal, or on-going dispute settlement proceedings involving that state, cease.

Languages

CRAMRA will have authentic texts in the four languages of the Antarctic Treaty -- English, French, Spanish and Russian --and in a new, fifth language, Chinese. The official working languages of the institutions remain the original four. Following the opening for signature of the Convention, certified copies (official translations) of the text in additional languages of other Parties may be provided by them and will be circulated to all Parties.

Commentary

I. How does the treaty deal with the basic disagreement over who owns Antarctica?

(the internal accommodation between claimant and non-claimant positions)

The fundamental attribute of sovereignty is the right to control what happens in national territory. Nations promulgate laws to regulate human activities that may be enforced not only against their own citizens and residents but also against visitors in their country. Those visitors take on the obligation of abiding by a nation's laws when they are permitted to enter it. Controlling and protecting natural resources is part of controlling what happens in one's territory. Thus the right to regulate minerals development falls squarely within the rights of sovereignty. If the seven nations claiming territorial sovereignty in Antarctica were to push their claim to the extreme, they would make the case that they had the exclusive right to regulate minerals development in their Antarctic territories, including the right to permit and restrict such development, to tax it, and to enforce applicable national laws. The rest of the nations taking part in the negotiations do not recognize the claims, and if they were to push their position to the extreme, they would see their task as one of drafting a regulatory system for Antarctic minerals development starting from the basis of nationality; that is, that the right to regulate minerals activities in Antarctica rests with the flag state of the operator. Distinctions between the rights and obligations of claimant and non-claimant states would be irrelevant.

Once the question of minerals development in Antarctica was broached, the ATCPs had to consider whether it was possible to marry these two positions in a manner that would be acceptable to both. There was some discussion of 'dividing up' the attributes of sovereignty. For example, one could assign the right to permit and monitor minerals activities to a claimant nation, and the right to tax revenues to the state whose company was undertaking the activity. Or one could divide between them the right to permit and tax the activity, granting enforcement authority to the sponsoring state. The variations are endless, but they were inevitably unsatisfactory to one or the other of the two most directly interested countries, the claimant and the flag state of the operator. Moreover, since the negotiations were not taking place on a bilateral basis, this 'division' of responsibilities had to be placed within the context of the larger group of negotiators, whose national interests spanned that of environmental protection, acquiring minerals and revenues, taking part in any minerals development projects, and/or having a strong voice in decision-making.

From the outset, therefore, the negotiations focused on the role of the institutions established by the Convention as a vehicle for addressing claimant/non-claimant concerns -- their composition, their powers and functions, the relationships between the institutions, and the voting procedures according to which decisions were taken. The conceptual cornerstone for this discussion was the idea that institutions could be established, which would be composed of a subgroup of the full decision-making membership of the treaty, and assigned special responsibilities within a limited geographic area of Antarctica -- the Regulatory Committee.

The resulting internal accommodation is as follows:

First, the political interest of the claimant states is reflected in their obligatory membership on any Regulatory Committee whose area of competence lies within their claimed territory. Second, the primacy of the claimant/non-claimant division of interests is reflected in the two chambers created within a Regulatory Committee -- the four-nation claimant group and the six-nation non-claimant group (which includes the United States and the USSR that maintain a basis of claim) -- and the special chambered voting procedures required for adoption of general requirements and decisions on exploration and development (Articles 29 and 32). Third, the relevant claimant state(s), together with the relevant sponsoring state, is granted a special role in examining an application and preparing a Management Scheme (Article 46).

At the same time, the general interests of all states Parties to the Convention are protected by the functions of the plenary Commission and the Advisory Committee vis-a-vis the Regulatory Committee. Where the

claimants opted for more discretionary powers being assigned the Regulatory Committee, wary of the predominant non-claimant membership of the Commission, the non-claimants sought a strong role for the Commission in issuing directives to and reviewing Regulatory Committee actions. The Commission can set the parameters for rule-making by the Regulatory Committee, and it can review certain of its actions to verify that they are consistent with Convention provisions. Thus neither the claimant nor the sponsoring state within the Regulatory Committee, nor the Committee as a whole, in adopting regulations and approving exploration and development activities, have blanket discretion to negotiate their own deal; they must do so within the context of the powers and functions assigned to the plenary Commission and subject to Advisory Committee evaluation of relevant environmental and technical factors. Each Management Scheme must be adopted by the full Regulatory Committee, whose members must determine that the proposal is consistent with general requirements as they have been adopted by the 10-member Regulatory Committee. These general requirements are themselves subject to the provisions of the Convention and relevant implementing rules and regulations developed by the Commission (Articles 47, 43, 41, 21). Moreover, the implementing regulations adopted by the Regulatory Committee must be promulgated before any applications are received, so that potential applicants may know the terms and conditions they must comply with before they submit applications, and to prevent discriminatory treatment among different applicants (Article 43). Finally, the review functions noted above permit either the Commission (Articles 19 and 49) or a dispute settlement procedure (Article 59) to review certain decisions by the Regulatory Committee, circumscribing its decision-making authority.

These provisions protecting the general interests of all Parties are balanced by provisions granting discretion to the institutions, which in turn could be interpreted to benefit a claimant state. For example, the Commission may adopt general regulations circumscribing any of the terms and conditions to be completed by the Regulatory Committee, but it is not obliged to (Article 41). This could allow the Regulatory Committee some leeway in interpreting Convention provisions and standards. And the door is left open for some negotiation in the preparation of a Management Scheme, since the specific terms and conditions promulgated by the Regulatory Committee obviously have to be interpreted in respect of a given application to reflect differences in mineral type, equipment and methods used, etc. Thus the claimant state and the sponsoring state, subject to Regulatory Committee approval, may come to some additional understanding, for example, with respect to financial obligations of operators or specific assignment of enforcement and dispute settlement responsibilities. In addition, as part of the final compromises in the negotiations, the review authorities noted above are not unlimited, and some of them require a high majority vote. This restricts the extent to which Regulatory Committee decisions may be challenged. (See section on Dispute Settlement/Review.)

On the financial side, there is the provision that in disposing of any surplus revenues, the Commission must ensure *inter alia* that the interests of the most directly interested members of the Regulatory Committee "are respected" (Article 35). This allows a claimant state to seek a special share of revenues, subject to consensus approval in the Commission.

Finally, the fact that any Commission member may inspect minerals activities, initiate a binding dispute settlement procedure and call for expedited provisional measures, as noted above, protects all Parties (Articles 12, 57, 58, and Annex, Article 6). A claimant state may interpret these provisions as particularly responsive to its concern that one state be able to challenge activities, i.e. in its claimed area. These provisions may equally serve non-claimant interests. The same is true for the right of any Regulatory Committee member to request a review of a decision to identify an area, although this is circumscribed by the 3/4 decision-making majority required in the Commission to refer the decision back to the Committee (Article 49).

II. How does the treaty deal with the concerns of the wider international community and the developing nations?

(the external accommodation)

There are four aspects to the external accommodation: the role granted the non-decision-making Parties to the Convention (non-Commission members), the provisions benefitting developing nations, the provisions on observer participation and public availability of information, and the respective roles of the CRAMRA and the International Seabed Authority (ISA) contemplated in the 1982 UN Convention on the Law of the Sea.

Non-Commission Members

The section on 'Institutions' above notes that full decision-making membership in the Commission (and thus the right to become a member of a Regulatory Committee) is based on a 'substantial activities' criterion parallel to that under the 1959 Antarctic Treaty. Thus the 'two-tier' system of decision-making criticized by some members of the international community in the United Nations General Assembly has been replicated in the minerals treaty. (The critics object to the fact that all nations do not enjoy equal standing under the Antarctic Treaty System, and that decision-making status carries a price tag of the expenditure of a significant amount of funds on Antarctic activities.) On the other hand, all Parties to the minerals treaty may undertake minerals activities in conformity with the Convention and are full members of the Advisory Committee and the Special Meeting of States Parties. They may also take part in Commission and Regulatory Committee meetings as observers. The Non-Commission members would have preferred a decision-making role for the Special Meeting of States Parties in identification of areas. If observer status works out as it has under the Antarctic Treaty, observers will be able to receive all documentation and to participate fully in deliberations. The restriction on their right to vote does not impede their taking part in any and all discussions.

Non-Commission members also negotiated the right to propose amendments to the Convention, but adoption and entry into force of these amendments requires approval by all Commission members.

Developing Nations

The developing nation interest group is a new one to Antarctic policymaking. Prior to the minerals treaty negotiations, no special role or special privilege for developing nations had been sought in ATCM deliberations or Antarctic activities (except that, as noted above, the developing nations have criticized the two-tier decision-making structure in the UNGA debates since 1983). As the minerals negotiations progressed, four developing nations acquired ATP status under the Antarctic Treaty and thus a full decision-making role in the minerals negotiations: Brazil, China, India, and Uruguay. They sought special consideration of developing nation interests as they are generally dealt with in other international fora. This issue is considered part of the 'external' accommodation because it first arose before these nations began to actively participate in the negotiations. Once they did, the negotiating forum adjusted to take account of their interests. The issues were resolved as follows:

Institutions

The developing nations (other than claimants Chile and Argentina) had sought a strong role for the Commission in all decisions, especially approval of exploration and development activities, in order to counteract any special accommodations that might be fashioned for sponsoring or claimant states in Regulatory Committee 'deals'. On this issue, their interests are protected in the same manner described above with respect to non-claimant state interests -- by the respective powers and functions allocated to the plenary Commission, advised by the Advisory Committee and the Special Meeting of States Parties, vis-a-vis those of the limited membership Regulatory Committees. Second, as noted in the description of the Regulatory Committee above, the Convention provides that at least three developing nations must be members of each Regulatory Committee (bearing in mind that Chile and Argentina are claimant nations and thus have automatic membership on Committees relevant to their claimed territories) (Article 29), and that this developing nation minimum may be reviewed as the proportionate membership of developed/developing nations may change with increasing Commission membership (Final Act). The Final Act also notes that Regulatory Committee decisions should include at least one developing nation in the required majority.

Participation in Activities

With respect to actually participating in minerals activities, the Convention provides that opportunities for joint ventures or other forms of participation, up to a defined level, must be elaborated at the time an area is identified for exploration and development activities (Articles 6 and 41), and that each application for such activities must indicate how it would comply with these measures (Article 44). Opportunities for such participation are designed for the particular benefit of developing nations, among others. Second, the Convention provides that measures for resolving competing applications, all other requirements and conditions being met, should include priority for the application with the broadest participation. Third, the Convention gives the Advisory Committee a role in promoting participation in minerals activities by developing nations, by advising them on relevant technical and scientific information, related training programs, and opportunities for

cooperation with other Parties (Article 26).

Financial Provisions

With respect to benefitting from revenues generated by minerals activities, the Convention provides that the Commission, in disposing of any surplus revenues, shall promote scientific research and developing nation participation in that research (Article 35). The stipulation that the Commission will adopt an alternative to equal sharing of budget contributions as soon as it is able also reflects developing nations' concerns that budget assessments be based on some other formula reflecting ability to pay.

Observer Participation/Public Availability of Documents

What was referred to above as the 'sunshine' provisions in the minerals treaty respond to different nations' and the public interest in knowing what is going on in Antarctica. These provisions are described in the sections on 'Institutions', 'Stages: Safeguards', and Compliance/Enforcement. They cover both participation by observer organizations in the institutions of the regime and the public availability of information and reports from these institutions. They also cover the requirement that both the Commission and the Advisory Committee give advance public notice of Advisory Committee meetings. In addition, there is a provision permitting the Advisory Committee, in preparing its advice, to seek information and advice from scientists and experts or scientific organizations on an ad hoc basis (Article 26), and one requiring the Commission, as appropriate, to cooperate with the United Nations, its relevant Specialized Agencies, and, as appropriate, the International Union for the Conservation of Nature and Natural Resources and other relevant international organizations, including non-governmental organizations, having a scientific, technical, or environmental interest in Antarctica (Article 34).

Respective CRAMRA/ISA Roles

In relation to concern expressed in the United Nations about the respective roles of the International Seabed Authority (ISA) contemplated in the 1982 UN Convention on the Law of the Sea to regulate seabed minerals development in the deep seabed beyond national jurisdiction, and the role of the CRAMRA in regulating Antarctic minerals development activities, the CRAMRA specifically limits its regulation of seabed mineral resource activities to those taking place on continental shelves, defined pursuant to criteria identified in the LOS Convention (Article 5 and Final Act). In addition, the Commission is to cooperate with any international organization competent to deal with mineral resource activities in areas adjacent to those covered by the CRAMRA, i.e., the ISA once established (Article 34).

Assessment

The sum total of these provisions represents a balance. They do not go so far as to change the two-tier decision-making structure employed elsewhere in the ATS, which has been challenged in the United Nations. They do for the most part permit non-Commission members and international organization observers to participate fully in deliberations in all of the institutions of the regime (with the exceptions that international organization observers in Regulatory Committees are not provided for, and that when issues of compliance are raised they are not immediately made known to international organization observers). They also provide for a substantial public record of the institutions, again with the exception of the Regulatory Committee, although they do not spell out state/operator reporting requirements with respect to exploration and development. They go further than any other international treaty in calling for an organization to give advance public notice of its meetings and issues under consideration, although the specific implementation of this latter is subject to rules yet to be adopted by the institutions. In relation to developing nation participation in actual minerals activities and benefits therefrom, the Convention is to promote such opportunities, but does not require that developing nations must participate in them.

III. How does the treaty deal with major environmental concerns?

The key to evaluating how the minerals treaty addresses major environmental concerns lies in understanding the fundamental legal requirements with which all proposed minerals activities must conform if they are to be judged acceptable: the standards and principles set forth in the Convention. These standards and principles are to be given effect by the institutions. Thus the decision-making procedures are integral to the effective application of the standards and principles. The interpretation of the standards and principles is also

integral to their effective application. The institutions will have to specify the information required and the criteria to be used in making determinations about the acceptability of minerals activities and promulgating measures to regulate them.

Another key element in protecting the Antarctic environment and dependent and associated ecosystems is the effectiveness of the provisions to ensure compliance. These are addressed above in the sections on 'Stages: Safeguards' and 'Compliance/Enforcement and Dispute Settlement/Review'. They are related, as noted in that section, to the 'sunshine' requirements in the treaty; that is, to the ability of observers and the public to review and influence the implementation of the treaty.

At a more fundamental level, the issue has been posed that the very existence of the CRAMRA makes it possible, since there is now an agreed legal regime, for minerals activities to take place in Antarctica. This is true. The alternative posed is that without an agreed legal regime, most nations/operators would be unlikely to undertake Antarctic minerals activities because of the uncertain legal situation. Other possible alternatives, however, are that in the event of a major discovery of minerals and/or sufficient need on the part of a nation/operator, that nation/operator would proceed, subject only to its national law; or that a country interested in conducting minerals activities might enter into a bilateral agreement with the relevant claimant, giving rise to disputes over territorial claims in Antarctica. To the extent that national laws are applicable in either case, they are likely to be far less effective in protecting the Antarctic environment than the standards and principles set forth in the CRAMRA.

Another argument used against the CRAMRA is that once minerals activities are permitted, they are likely to lead to disputes in Antarctica and potential environmental damage. Yet if nations/operators proceed on the basis of national law or bilateral agreements, these situations are far more likely to lead to disputes and accidents than under an agreed legal regime.

The Standards and Principles

The legal requirements governing the acceptability of all minerals activities are set forth in several different articles: Article 2 (Objectives and General Principles), Article 4 (Principles Concerning Judgments on Antarctic Mineral Resource Activities), Article 13 (Protected Areas), Article 15 (Respect for Other Uses of Antarctica), and Articles 10 and 34 (Consistency with the Other Components of the Antarctic Treaty System and Cooperation with Other International Organizations). These provisions provide a very strong foundation on which to build effective environmental protection.

Data and Information

The most fundamental legal obligation is that found in Article 4(1):

Decisions about Antarctic mineral resource activities shall be based upon information adequate to enable informed judgments to be made about their possible impacts and no such activities shall take place unless this information is available for decisions relevant to those activities.

While prospecting, as noted above, may proceed without specific authorization, any decision to identify an area or to approve exploration or development activities is subject to the adequacy of information requirement. Even with respect to prospecting, it is the sponsoring state's obligation to undertake an environmental impact assessment and to make judgments in accordance with the adequacy of information standard, and six other Commission members may challenge this judgment.

There is a general requirement that data and information obtained from mineral resource activities be made freely available, subject to confidentiality requirements for data and information of commercial value (Article 16 and 37). Moreover, because of the sufficiency of information requirement, there is an incentive for states to turn over as much information as may assist in making the judgments called for under the treaty. It is among the Advisory Committee's expert functions to identify the criteria and the types of data and information necessary to carry out the judgments. It is to be hoped that in adopting implementing measures on this subject, Commission and Regulatory Committee members will stress the adequacy of information requirement. A commitment on the part of Parties to fund relevant basic and directed research and monitoring programs will help build up the data and information necessary for decision-making.

Environmental Standards and Principles

Article 4 also specifies that no Antarctic mineral resource activity, including prospecting, may take place

until an environmental impact assessment has been completed and the judgment can be made (subject to the adequacy of information standard above) that the proposed activity would not cause:

- (i) significant adverse effects on air and water quality;
- (ii) significant changes in atmospheric, terrestrial or marine environments;
- (iii) significant changes in the distribution, abundance or productivity of populations of species of fauna or flora;
- (iv) further jeopardy to endangered or threatened species or populations of such species;
- (v) degradation of, or substantial risk to, areas of special biological, scientific, historic, aesthetic or wilderness significance, or
- (vi) significant adverse effects on global or regional climate or weather patterns.

In addition, it requires that no mineral resource activity take place until it is judged (subject to the adequacy of information standard) that:

- (i) technology and procedures are available to provide for safe operations and compliance with the six standards noted above, and
- (ii) there exists the capacity to monitor key environmental parameters and ecosystem components so as to identify any adverse effects and to provide for necessary modifications.

These judgments must take into account the cumulative impacts of Antarctic mineral resource activities, in combination with possible impacts from other uses of Antarctica.

Environmental Impact Assessment

Operators submitting prospecting notifications or applications for exploration or development, and any state Party submitting a notification for identification of an area, must include a detailed assessment of the environmental and other possible impacts. With the exception of prospecting, the Advisory Committee must evaluate the adequacy and completeness of these submissions and undertake a comprehensive environmental and technical assessment of the proposed actions, based on considerations set forth in the Convention that parallel requirements under US law for an environmental impact statement (Article 26(4)). The promulgation by the Regulatory Committee of the implementing rules and regulations for an identified area is also subject to this comprehensive evaluation. As for prospecting, the safeguard procedure described above permits a minimum of six states, upon reviewing the assessment submitted, to request the Commission to convene and consider adopting regulations applicable to prospecting, on which Advisory Committee advice shall be sought (Article 38).

Protected Areas

The Convention prohibits outright any mineral resource activities in areas that under the Antarctic Treaty have been designated as Specially Protected Areas (SPAs) or Sites of Special Scientific Interest (SSSIs). The Commission may designate additional protected areas at any time, and must consider whether additional prohibitions or restrictions would be appropriate in a buffer zone adjacent to protected area designations. Moreover, the Convention requires the Commission to consider, at the time when it determines whether to identify an area for possible exploration or development, whether to restrict or prohibit activities in areas protected pursuant to other components of the Antarctic Treaty System. It is also under a presumption to prohibit activities in any type of protected area that may be adopted under the Antarctic Treaty, unless that measure provides otherwise. Protected areas designations are to be coordinated among all relevant institutions of the Antarctic Treaty System (Article 13).

Respect of Other Uses

One of the contentious debates that took place in the minerals negotiations was over whether there should be a presumption in the minerals treaty about priority of uses in Antarctica; that is, whether, for example, scientific research, wilderness values, or tourism in Antarctica should be accorded automatic priority over minerals development activities. The treaty does not resolve this issue, a priori. It does establish a binding legal obligation to respect other uses in Antarctica (Articles 2 and 15). In addition, it provides that the environmental assessments should take into account impacts on other uses of Antarctica and how to mitigate

or avoid them.

Coordination and Consistency

In order to ensure the achievement of the objectives and principles of the minerals treaty, and to avoid any interference with the achievement of the objectives and principles of other components of the Antarctic Treaty System, the Convention calls for cooperation and consultations by the Commission and the Advisory Committee, as appropriate, with Parties to the Antarctic Treaty and the Antarctic Seals Convention, with the Commission on Antarctic Marine Living Resources, and with the Scientific Committee on Antarctic Research. These provisions are particularly important to give effect to obligations to respect other uses and to coordinate protected areas designations (Articles 10 and 34).

The Role of the Advisory Committee

The Advisory Committee is granted a substantial role in providing advice on any and all decisions requiring scientific, technical, or environmental expertise. There has been some concern that Parties' designated representatives on the Advisory Committee may be subject to pressures to ignore their 'technical' role and provide opinions that reflect political decisions taken within their countries. There is no way to prevent this; it can only be guarded against by the 'sunshine' provisions in the regime and by the international and public pressure likely to result from abuse of their technical function. As noted above, the 'sunshine' provisions relating to Advisory Committee deliberations are exceptionally open. Second, the facts that the Advisory Committee is not a decision-making body, and that all views expressed must be reflected in its reports facilitates freedom of expression and debate.

There has also been some concern expressed that the Advisory Committee is not master of its own meetings and procedures, in that they are subject to approval by the Commission. Given the budgetary implications, this is not unusual. And any attempt by the Commission to curtail the Advisory Committee in its functions is also likely to be subject to adverse international and public pressure.

The Convention specifies that the Advisory Committee is to provide advice to the Commission and to the Regulatory Committee, as relevant to its areas of expertise, throughout the implementation of the principles and standards of the treaty; that is, with respect to any decision point where they must be applied (Article 26). As noted in the sections above:

the Advisory Committee role in reviewing notifications to identify an area and applications to carry out exploration or development is specifically referenced in the Convention (Articles 26, 40, 42, 45, 54);

with respect to applications for exploration and development, the Convention explicitly states that the Regulatory Committee must refer to the Advisory Committee all parts of the application which are necessary for it to provide advice, together with any other relevant information;

the role of the Advisory Committee is specifically referenced with respect to any decisions the Commission is called upon to make regarding prospecting activities (Articles 26 and 38).

The Advisory Committee has a role:

in reviewing inspection and monitoring reports and the general conduct of mineral resource activities to safeguard the Antarctic environment;

in advising both the Commission and Regulatory Committees in their preparation of implementing measures called for under the Convention, including the Regulatory Committee with respect to monitoring and assessment programs;

in advising the Commission on the designation of protected areas;

in advising the Regulatory Committee in relation to decisions to suspend, modify or cancel exploration or development activities in view of adverse environmental impacts (Article 51); and

with respect to scientific research and data collection activities related to mineral resource activities and the judgments called for under the treaty.

Decision-Making Procedures

Approval of Activities

The decision-making majorities required to adopt measures, to take decisions to identify an area, and to approve exploration or development activities are described elsewhere in this report. In the context of environmental considerations, it is worth highlighting that a decision to identify an area requires the consensus of all Commission members, a very stringent criterion. This means that if a single Commission member objects, the identification of the area as proposed is prohibited. The approval of exploration or development activities also requires a relatively high majority (2/3 of Regulatory Committee members (7 out of 10), including a simple majority of both claimants and non-claimants) (Articles 22 and 32).

When it comes to approving the final development stage of activities, the Regulatory Committee must, by a 2/3 chambered majority in each case, either (1) take a specific decision that modifications to a Management Scheme at the development stage are not necessary, or (2) agree on proposed modifications. Since it is likely that there would be significant changes from the less than detailed development activities proposed at the time of the adoption of the Management Scheme, some modifications will undoubtedly be necessary. This places the burden on those seeking modifications to obtain the necessary majority. The ultimate result from an environmental point of view, although this will depend on the leanings of the members of the Regulatory Committee, could agreement on less stringent environmental protections to avoid an impasse that may otherwise result (Article 54).

Adoption and Revision of Implementing Measures

In relation to implementing regulations, it is difficult to determine at this time how the procedures for their adoption and revision by the Commission (3/4 majority) and the Regulatory Committee (2/3 majority, including at least half of the claimant and non-claimant members) will operate with respect to environmental considerations. This depends on the relative importance attached to environmental considerations by the majority of decision-makers. If only a few members are particularly concerned about environmental protection, it will be difficult to obtain the required majority in support of stringent implementing measures. On the other hand, simple majority approval of regulations of this type would be unusual in international agreements, where it is generally applied only to procedural decisions.

Safeguards

The safeguards provisions discussed in earlier sections do appear to provide an adequate balance to protect environmental considerations. They must be evaluated against the general background of high majorities required for all decisions. Thus, while a single member of the Regulatory Committee, or six members of the Commission, may call for review of a decision to approve exploration or development, it requires the normal 3/4 majority to direct the Regulatory Committee to reconsider its decision. Review of prospecting activity requires six to convene the Commission and the 3/4 majority to adopt measures. Decisions to suspend, modify, or cancel exploration or development activities, or to impose monetary penalties, requires a simple 2/3 majority in the Regulatory Committee, without any additional chambered majorities. Finally, when disputes arise that are subject to binding procedures (which includes all disputes over measures related to protection of the Antarctic environment, prospecting, respect for other uses, and liability) any Party may, within specified time limits, request that the binding procedures be applied, as well as expedited consideration of provisional measures to protect the environment (Articles 49, 38, 51, 57 and 58, 22 and 32, and Annex, Article 6).

Liability

As noted earlier, the liability regime can be divided between that applicable prior to entry into force of a more detailed Protocol on liability, and that applicable afterwards. The topics to be covered by the Protocol have been described above. Because the Protocol must be adopted by consensus, any Commission member may prevent agreement on it. This effectively prevents any minerals exploration and development from going forward, because no such activity may be approved until the Protocol is in force for the applicant. As for the liability regime applicable to prospecting prior to entry into force of the Protocol, it is a stringent one in that operators have strict liability for environmental and other damages; the sponsoring state must ensure that its operators maintain the necessary financial and technical capacity to undertake any required response actions and to meet any potential liability; and the sponsoring state is required to ensure that response actions are undertaken to the extent that its operator fails to meet its obligations under the Convention for doing

so. Moreover, sponsoring states must ensure recourse to domestic courts as described in the section on liability (Articles 8 and 37).

What are some of the key issues to be considered in domestic ratification and implementing legislation?

Without going into great detail at this point, there are several elements of domestic implementing legislation that will be particularly important. It should also be noted that because the prospecting regime is somewhat distinct from that applying to exploration and development, in that prospecting is not automatically subject to decisions by the institutions, it would be appropriate to provide more detailed guidance in national implementing legislation to interpret the standards and principles of the Convention as they apply to prospecting. Moreover, domestic interpretations of these standards and principles could help set the standard for their ultimate interpretation by the institutions established by the CRAMRA.

Important elements for each nation to include in legislation:

- (i) establishing procedures for identifying the categories of data and information, and the criteria necessary to implement the principles and standards of the regime;
- (ii) establishing a mechanism to fund and undertake the basic and directed research and the monitoring programs necessary to collect the data and information required to effectively implement the standards and principles, and in US legislation to ensure effective inter-agency coordination to carry out this commitment, bearing in mind related Antarctic research programs and capabilities in the National Science Foundation and the National Marine Fisheries Service in NOAA;
- (iii) specifying in the legislation itself certain data and information requirements identifiable at this time, including the commitment to call for a survey to identify areas where minerals activities should be prohibited or restricted, pursuant to the Convention, prior to any decision to identify an area for possible minerals exploration and development;
- (iv) in US legislation, requiring full compliance with the National Environmental Policy Act (NEPA), in relation to any activities proposed by US-sponsored operators, including prospecting;
- (v) requiring opportunity for full public participation and comment in the promulgation of domestic regulations pursuant to implementing legislation, and in the determination of national policies with respect to pending decisions before the Commission and the Regulatory Committees, including provisions to give effect to the requirement in the Convention for advance public notice of matters before the Advisory Committee and transmission of relevant information to interested international organizations;
- (vi) requiring the maintenance at national Antarctic contact points of the public record provided for in the Convention;
- (vii) giving effect to the requirement in the Convention in relation to prospecting that the sponsoring state ensure that basic data and information of commercial value generated by prospecting be maintained in archives, and specifying the conditions under which part or all of this data and information must be released for scientific or environmental purposes;
- (viii) specifying in detail reporting requirements with respect to prospecting, exploration and development, in order to further compliance with the Convention;
- (ix) requiring a commitment to monitor and inspect minerals activities and otherwise to ensure compliance with the Convention;
- (x) specifying directions to negotiators with respect to important objectives to be attained in the negotiation of the liability Protocol; and
- (xi) specifically with respect to the liability regime for prospecting, to indicate:
 - (a) criteria and procedures to ensure that an operator maintains a substantial and genuine link with the sponsoring state and adequate financial and technical capabilities to comply with the Convention (Article 37(7));
 - (b) criteria and procedures to be used in determining the financial capacity an operator must maintain, "commensurate" with the nature and level of activity and the risks involved, in order to meet potential liability claims (Article 37(3)); and
 - (c) how the requirements for recourse to national courts for liability claims and Commission standing to pursue liability claims will be given effect (Article 8(10)).

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Appendix**Recommendation XI-1**

Buenos Aires, Argentina

July 1981

Antarctic Mineral Resources

The Representatives,

Recalling the provisions of the Antarctic Treaty, which established a regime for international co-operation in Antarctica, with the objective of ensuring that Antarctica should continue forever to be used exclusively for peaceful purposes and should not become the scene or object of international discord;

Convinced that the framework established by the Antarctic Treaty has proved effective in promoting international harmony in furtherance of the purposes and principles of the United Nations Charter, in prohibiting *inter alia* any measures of a military nature, in ensuring the protection of the Antarctic environment, in preventing any nuclear explosions and the disposal of any radioactive waste material in Antarctica, and in promoting freedom of scientific research in Antarctica, to the benefit of all mankind;

Convinced further of the necessity of maintaining the Antarctic Treaty in its entirety and believing that the early conclusion of a regime for Antarctic mineral resources would further strengthen the Antarctic Treaty framework;

Desiring without prejudice to Article IV of the Antarctic Treaty to negotiate with the full participation of all the Consultative Parties to the Antarctic Treaty an appropriate set of rules for the exploration and exploitation of Antarctic mineral resources;

Noting the unity between the continent of Antarctic and its adjacent offshore areas;

Mindful of the negotiations that are taking place in the Third United Nations Conference on the Law of the Sea;

Reaffirming their commitment to the early conclusion of a regime for Antarctic mineral resources which would take due account of the respective interest of the Consultative Parties as regards the form and content of the regime, including decision-making procedures, as well as the special characteristics of the Antarctic area;

Recalling Recommendations VII-6, VIII-I4, IX-I and X-I;

Recalling further Recommendations VI-4, VII-I, VIII-II, VIII-I3, IX-5, IX-6 and X-7;

Recommend to their Governments that:

1. They take note of the progress made toward the timely adoption of a regime for Antarctic mineral resources at the Eleventh Consultative Meeting and related meetings and the importance of this progress.

2. A regime on Antarctic mineral resources should be concluded as a matter of urgency.

3. A Special Consultative Meeting should be convened in order:

(a) to elaborate a regime;

(b) to determine the form of the regime including the question as to whether an international instrument such as a convention is necessary;

(c) to establish a schedule for negotiations, using informal meetings and sessions of the Special Con-

sultative Meeting as appropriate; and

(d) to take any other steps that may be necessary to facilitate the conclusion of the regime, including a decision as to the procedure for its adoption.

4. The Special Consultative Meeting should base its work on this Recommendation and the relevant Recommendations and Reports of the Eighth, Ninth and Tenth Antarctic Treaty Consultative Meetings.

5. The regime should be based on the following principles:

(a) the Consultative Parties should continue to play an active and responsible role in dealing with the question of Antarctic mineral resources;

(b) the Antarctic Treaty must be maintained in its entirety;

(c) protection of the unique Antarctic environment and of its dependent ecosystems should be a basic consideration;

(d) the Consultative Parties, in dealing with the question of mineral resources in Antarctica, should not prejudice the interests of all mankind in Antarctica;

(e) the provisions of Article IV of the Antarctic Treaty should not be affected by the regime. It should ensure that the principles embodied in Article IV are safeguarded in application to the area covered by the Antarctic Treaty.

6. Any agreement that may be reached on a regime for mineral exploration and exploitation in Antarctica elaborated by the Consultative Parties should be acceptable and be without prejudice to those States which have previously asserted rights of or claims to territorial sovereignty in Antarctica as well as to those States which neither recognize such rights of or claims to territorial sovereignty in Antarctica nor, under the provisions of the Antarctic Treaty, assert such rights or claims.

7. The regime should *inter alia*:

(i) Include means for:

(a) assessing the possible impact of mineral resource activities on the Antarctic environment in order to provide for informed decision-making;

(b) determining whether mineral resource activities will be acceptable;

(c) governing the ecological, technological, political, legal and economic aspects of those activities in cases where they would be determined acceptable, including:

-the establishment, as an important part of the regime, of rules relating to the protection of the Antarctic environment; and

-the requirement that mineral resource activities undertaken pursuant to the regime be undertaken in compliance with such rules.

(ii) Include procedures for adherence by States other than the Consultative parties, either through the Antarctic Treaty or otherwise, which would:

(a) ensure that the adhering State is bound by the basic provisions of the Antarctic Treaty, in particular Articles I, IV, V and VI, and by the relevant Recommendations adopted by the Consultative Parties; and

(b) make entities of that State eligible to participate in mineral resource activities under the regime.

(iii) Include provisions for co-operative arrangements between the regime and other relevant international organizations.

(iv) Apply to all mineral resource activities taking place on the Antarctic Continent and its adjacent off-shore areas but without encroachment on the deep seabed. The precise limits of the area of application would be determined in the elaboration of the regime.

(v) Include provisions to ensure that the special responsibilities of the Consultative Parties in respect of the environment in the Antarctic Treaty Area are protected, taking into account responsibilities which may

be exercised in the area by other international organizations.

(vi) Cover commercial exploration (activities related to minerals involving, in general, retention of proprietary data and/or non-scientific exploratory drilling) and exploitation (commercial development and production).

(vii) Promote the conduct of research necessary to make environmental and resource management decisions which would be required.

8. They promote and co-operate in scientific investigations which would facilitate the effective operation of the regime taking into account, *inter alia*, the relevant parts of the Report of Ecological, Technological and other Related Experts on Mineral Exploration and Exploitation in Antarctica (Washington, June 1979), attached as an annex to the Report of the Tenth Consultative Meeting.

9. With a view to improving predictions of the environmental impacts of activities, events and technologies associated with mineral resource exploration and exploitation should such occur, they continue with the assistance of the Scientific Committee on Antarctic Research, to define programs with the objectives of:

(a) Retrieving and analyzing relevant information from past observations and research programs;

(b) Ensuring in relation to the needs for information identified by the Experts Report, that effective use is made of existing programs;

(c) Identifying and developing new programs that should have priority, taking account of the length of time required for results to become available.

10. In elaborating the regime, they take account of the provisions of Recommendation IX-I, paragraph 8.