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**MINERALOGY AND PETROLOGY OF THE SITTAMPUNDI COMPLEX
SALEM DISTRICT, MADRAS STATE, INDIA**

**ANANTHARANA
PARAMESWARA
A. P. SUBRAMANIAM**
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CONTENTS

	<u>Page</u>
PREFACE.	viii
ABSTRACT	xi
CHAPTER I - LOCATION AND HISTORICAL REVIEW	1
Introduction, location.	1
Historical review	2
Present Study	8
CHAPTER II - REGIONAL GEOLOGY AND THE SETTING OF THE COMPLEX	10
Archaean Geology of Peninsular India.	10
Geology of the Anorthosite-eclogite gabbro complex	18
Structure of the complex.	22
CHAPTER III - MINERALOGY	24
Introduction, methods of separation, and determination of optical properties	24
Explanation of tabular statement of analyses of minerals.	31
Garnets	33
Plagioclase Feldspars	42
Clinzoisite.	57
Cordierite	63
Anthophyllite	70
Climo-amphiboles.	73
Chromite.	83
Pyroxenes	89
Scapolite	91
Corundum, sillimanite, rutile, sphene, etc.	92
Summary.	94

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87
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CHAPTER IV - PETROGRAPHY	95
Anorthosite series-general description.	95
Description of principal types	102
Chromitites	108
Cordierite-corundum-anthophyllite-anorthite-bytownite rock. . .	109
Eclogite gabbro series-general description.	110
Description of principal types.	113
Retrograde characters of eclogites.	117
Pyroxenite - Websterite	119
Amphibolite	120
CHAPTER V - CHEMICAL GEOLOGY AND METAMORPHISM	125
Anorthosite series	125
Epidote-plagioclase equilibrium	127
Metamorphic facies.	128
Cordierite-corundum-anthophyllite-anorthite-bytownite rocks . .	129
Problem of the eclogites.	130
Eclogite rocks of the Sittampundi complex	133
(FeO+MnO), MgO, CaO, diagram.	134
Origin of eclogites	137
Metamorphism of the complex as a whole	139
Origin of chromite	141
Origin of corundum	143
Origin of banding in the complex	145
Preferred orientation of minerals	147
CHAPTER VI - PETROGENESIS	149
Comparison with stratiform sheets and evidence for igneous origin of the complex	149
Summary	152
BIBLIOGRAPHY	155

TABLES

	<u>Page</u>
I. Chemical composition and physical and optical properties of some minerals from the Sittampundi complex	32A
II. Composition and physical properties of Garnet C.12	34
III. Physical properties of Garnet and members Refractive indices of some garnets with estimated composition and the compositions of associated plagioclase and orthopyroxene	36
IV. Composition and physical properties of Garnet C.41	37
V. Composition and physical properties of Garnet C.60	38
VI. Chemical composition and physical properties of eclogite garnets	39
VII. Chemical composition of anorthite from Sittampundi Partial spectroscopic analyses of some anorthitic feldspars	44
VIII. Chemical composition and physical properties of some anorthites	45
IX. Anorthite content of plagioclases in Sittampundi rocks by various methods	50
X. Twinning Laws of Plagioclase Feldspars in the Sittampundi Rocks	53
XI. Analyses of clinozoisite from Anorthite-corundum rocks of Salem	58
XII. Composition of clinozoisite C.39	59
XIII. Molecular formula and physical properties of clinozoisite C.39	60
XIV. Chemical composition and physical properties of some clinozoisites	61
XV. Composition of Cordierite C.71	64
XVI. Composition and physical properties of some magnesian cordierites	65
XVII. Composition and optical properties of Cordierite C.71	66
XVIII. Composition of Anthophyllite C.58	71
XIX. Composition of amphibole C.34	74
XX. Composition of amphibole C.70	75
XXI. Composition of amphibole from rock C.33 (calculation)	76
XXII. Composition of amphibole C.33	77
XXIII. Structural account of the analyzed amphiboles, after Sundius, indicating affinities to the Edenite and Fargasite type	78

XXIV.	Optical and physical properties of analyzed amphiboles	79
XXV.	Optical properties of some amphiboles	80
XXVI.	Composition of Chromite from Chromitite C.101	85
XXVII.	Calculation of atoms per unit cell of chromite C.101	86
XXVIII.	Chemical composition of some chromites from stratiform sheets	87
XXIX.	Approximate modes of rocks from the Sittampundi complex(weight%)	96
XXX.	Chemical composition with normative and modal mineralogical composition of some rocks from the Sittampundi complex	120
XXXI.	Analyses of anorthosites from South Africa, Sweden, and Sittampundi Complex	123
XXXII.	Chemical composition of Eclogite gabbro C.41, together with comparable analyses	124
XXXIII.	Molecular ratios (FeO+MnO), CaO, and MgO of Gabbroic and eclogitic rocks, together with those of the garnets in them in so far as available, recalculated to 100%	135
XXXIV.	Comparative vertical sequence in some gravity stratified sheet complexes	150

ILLUSTRATIONS

<u>Plate</u>	<u>Between Pages</u>
I.	3-4
i) View of ancient corundum workings on anorthosite band, south of Sittampundi. Note barren nature of country.	
ii) Low hill of anorthosite north of Kattipalaiyam, towards the N.E. end of complex.	
II.	18-19
i) Steeply dipping anorthosite near Pamandapalaiyam.	
ii) Anorthosite outcrop east of Kattupaliyam, note lower dip.	
III.	18-19
i) Foliated amphibolite on northern margin of complex, south of Kanasamudram.	
ii) Typical exposure of weathered anorthosite south of Sittampundi.	
IV.	20-21
i) Typical exposure of anorthosite with mafic bands on high ground south of Sittampundi.	
ii) Outcrop of eclogite-gabbro near Gangarapalaiyam, note visible foliation.	
V.	20-21
i) Anorthosite with mafic layers, near Molasi, western end of complex.	
ii) Large band of hornblende rock in anorthosite, outcrop near Sanarpalaiyam.	
VI.	20-21
i) Banded anorthosite near Syakkadupudur	
ii) Mafic bands in anorthosite, outcrop near Mannadipalaiyam.	
VII.	21-22
i) Pseudo-Boudinage structure of mafic bands in anorthosite, outcrop north of Kattipalaiyam	
ii) Seam of chromitite in old corundum quarry at Karungalpatti	
VIII.	21-22
i) Jointing in chromitite at Karungalpatti quarry.	
ii) Jointing in chromitite at Karungalpatti quarry.	
IX.	21-22
i) Jointing in anorthosite, old corundum quarry south of Sittampundi.	
ii) Jointing in anorthosite outcrop at Kottakkaradu east of Karungalpatti.	
X.	22-23
Diagrammatic interpretation of the form and structure of Complex.	

XI.	34-35
i) Photomicrograph, showing garnet replacing anorthite. X 10	
ii) Photomicrograph, showing garnets with dactylitic rims, in eclogite-gabbro. X 35	
XII.	34-35
Micrograph showing garnet selectively replacing anorthite.	
XIII.	41-42
Micrograph of garnet in eclogite gabbro, with plagioclase hornblende symplectite.	
XIV.	41-42
Micrograph of garnet crystal in eclogite gabbro	
XV.	48-49
Curve correlating the indices of refraction and 'An' content for calcic plagioclase indicating position of Sittampundi plagioclases.	
XVI.	51-52
Photomicrograph of anorthite clinozoisite rock showing a crystal of anorthite displaying complex albite-Ala twinning. X 22	
XVII.	61-62
Micrograph showing replacement of anorthite by clinozoisite	
XVIII.	61-62
Micrograph showing well developed crystal of clinozoisite in anorthite gneiss.	
XIX.	66-67
i) Photomicrograph of zoned crystal of clinozoisite. X 50.	
ii) Photomicrograph of cordierite showing twinning. X 100.	
XX.	66-67
Sketch of exposure of footwall of old dorundum quarry south of Sittampundi, showing paragenetic relationship of corundum, clinozoisite, garnet, and anorthite.	
XXI.	71-72
i) Photomicrograph showing bladed anthophyllite in anorthosite. X 9	
ii) Photomicrograph showing bladed anthophyllite in chromitite. X 10	
XXII.	71-72
Micrograph showing anthophyllite in anorthosite.	
XXIII.	82-83
Curves expressing the optical properties of hornblendes from Sittampundi rocks, in relation to their chemical composition.	
XXIV.	87-88
i) Photomicrograph of polished section of chromite with rutile. X 180.	
ii) Photomicrograph of polished section of chromite with plates of unknown mineral, note their geometric orientation. X 400	

XXV.	Triangular diagram after Stevens, showing position of Sittampundi chromite.	88-89
XXVI.	i) Photomicrograph-skeletal crystals of diopside in anorthosite. X.22. ii) Photomicrograph-Ilmenite, rutile and apatite in anorthosite, X.7.	90-91
XXVII.	Micrograph of skeletal crystals of diopside in anorthosite showing paramorphic alteration to edenite.	90-91
XXVIII.	Micrograph of corundum replacing anorthite.	91-92
XXIX.	i) Porphyroblast of corundum in anorthosite. ii) Porphyroblast of corundum in anorthosite.	96-97
XXX.	i) Coarse anorthosite with anthophyllite ii) Chromitite layer in hand specimen of anorthosite.	103-104
XXXI.	i) Photomicrograph of anorthosite displaying mosaic texture. X 10 ii) Photomicrograph of anorthosite showing preferred orientation. X7	105-106
XXXII.	i) Photomicrograph of eclogite gabbro. X 9 . ii) Photomicrograph of bytownite gneiss. X 7.	105-106
XXXIII.	Micrograph of eclogite	114-115
XXXIV.	Micrographs of garnet coronas in eclogite	114-115
XXXV.	i) Photomicrograph of eclogite gabbro. X 10 ii) Photomicrograph of bronzitic pyrope. X 10	114-115
XXXVI.	A C F Diagram for Amphibolite facies.	128-129
XXXVII.	A C F Diagram for Sanidinite facies	129-130
XXXVIII.	A C F Diagram for Eclogite facies.	133-134
XXXIX.	(FeO+MnO), MgO, CaO diagram.	133-134
XL.	Petrological map of Sittampundi complex.	In pocket.

PREFACE

During my official duties with the Geological Survey of India, I had opportunities to make a fairly detailed field study of a group of basic rocks from the Archaean complex of Peninsular India. The results presented in this dissertation are the outcome of laboratory studies of these rocks, carried out in the Department of Geology, Princeton University, for the last two years.

I am deeply grateful to the Graduate School, Princeton University, for the award of Scholarship and Fellowship for the academic years 1949-50, and 1950-51, covering the cost of tuition, and the Department of Geology for generous grants, covering the cost of 18 chemical analyses of rocks and minerals, 60 thin sections, and the illustrations in this paper.

I am under a deep debt of gratitude to Professors A. F. Buddington and H. H. Hess, under whose general supervision this investigation was carried out. Their stimulating discussions of the problem and helpful criticisms of the manuscript have greatly contributed to this study. The mineralogical and petrographic studies were carried out principally under the generous guidance of Professor Hess, and I am indebted to him for initiating me in several optical methods with which I was unfamiliar. To Professor E. Sampson, my thanks are due for useful discussions on the chromite problem and for introducing me to the study of polished sections. I am specially obliged to him for the photomicrographs in Plate XXIV, and for polishing some of my chromites for microscopic study. My thanks are also due to Dr. J. C. Maxwell for discussing some aspects of my problem and for various suggestions, much appreciated by me. To the other members of the faculty I am most grateful for the encouragement I have received

during my studies. To Mr. J. R. Smith I am grateful for helping me in determining the a^0 constant for the analyzed garnets.

It is a pleasure to acknowledge my gratitude to Dr. N. L. Bowen for his interest in the calcic plagioclases in my rocks, and for determining the composition of a few specimens by the new X-ray method, developed at the Geophysical laboratory. I am very much indebted to Dr. J. R. Goldsmith of the University of Chicago for determining the melting point of the analyzed specimen of anorthite, and for arranging to ~~make~~ partial spectroscopic analyses of 12 specimens of calcic plagioclase. To his colleague, Mr. O. Joensuu, spectroscopist at the University of Chicago, I am equally grateful, for making these analyses.

To Dr. S. S. Goldich and Mrs. Eileen K. Oslund, of the Rock Analysis Laboratory, University of Minnesota, I am grateful, for the care and time they have devoted to the analyses of minerals and rocks described in this paper. To Drs. Robert Balk, A. L. Howland, J. W. Peoples and T. P. Thayer, my thanks are due for the benefit I derived from brief discussions with them on my problem.

To Dr. M. S. Krishnan, presently Director, Geological Survey of India, I am most grateful for suggesting this problem and visiting me in the field during field studies, and for help in numerous other ways. My thanks are due to my colleague, Mr. N. K. N. Aiyengar, for introducing me to the geology of the Salem district.

To Miss M. R. Law and her associates in the departmental office and to Miss G. Cobb and her colleague in the library, I am thankful for the courtesy and help I have received during the last two years. My special thanks are due to Mrs. C. Sadlon for preparing several excellent thin sections and also for translating a few Russian references.

The results presented in this paper represent only a beginning in a detailed regional study of the Archaean rocks of Peninsular India. It is my hope that future studies will bring out the relationship of the Sittampundi Complex to the regional geology, and also elucidate the eclogite and charnockite problems. More detailed field and laboratory studies of the Complex must be undertaken before many problems of its genesis can be solved.

ABSTRACT

This dissertation embodies the results of field and laboratory studies on a group of basic rocks from the Archaean complex of Peninsular India. These studies indicate the rocks to be a part of a gravity stratified sheet, which have undergone profound metamorphic transformations after their primary crystallization from a basic magma.

Mineralogy

Ten minerals from the various rocks have been studied in some detail to elucidate the genesis of these rocks. Two garnets from the rocks of the eclogite gabbro series were found to be rich in pyrope molecule, and hence considered eclogite garnets. A garnet from the anorthosite was found to be rich in grossularite molecule with a fair abundance of the pyralmandite molecule.

The plagioclases in the anorthositic rocks were found to be mostly bytownite-anorthites. Chemical analysis of one specimen and partial spectroscopic analyses of 12 specimens, indicate them to vary in composition from An_{80} to An_{99} . It is believed that some of these rocks contain plagioclase with the highest 'An' content known so far. As anorthite feldspar was described and identified from these rocks by Count de Bournon in 1802, and named indianite, it is proposed that the name be revived to indicate natural feldspars of composition $An_{90}-An_{100}$, restricting the name anorthite to the end molecule hitherto unrecorded in nature. The optical studies on these feldspars have shown that the indices of refraction are sensitive to small changes in composition and hence are critical for the accurate estimation of the composition of plagioclase feldspars.

Anthophyllite occurring in some anorthosites was found to be an aluminian variety. The optical properties of this and other aluminian anthophyllites do not fit Rabbitt's curve. It is thought that the name gedrite should be retained for the aluminian anthophyllites.

The monoclinic amphiboles occurring as the principal mafic mineral in the anorthosites and related chromitites were found to be edenite and pargasite respectively, and thought to form a sub-series under the hornblende series.

The cordierite occurring in a peculiar corundum-cordierite assemblage, was found to be magnesian in composition with the normal optically negative character. An analysis of existing data from the literature on the composition and optical properties of cordierite shows that the optically anomalous character of the mineral cannot be attributed to the presence of alkalis, lime, etc. as contended by previous workers.

The clinozoisites present in the anorthositic rocks are low in epidote molecule, but show compositional variation within the same rock, and occasionally within the same crystal.

The chromite in the chromitite was found to be an aluminian variety, approaching a chromian spinel.

The corundum invariably present in the anorthositic rocks is interpreted to be secondary, being derived from the primary minerals during the two periods of metamorphism.

Petrology

The complex consists of a layered sequence of anorthosites, with chromitite and perknite bands, and eclogite gabbros. By analogy with other described occurrences of stratiform sheets, this is interpreted as a gravity stratified layered complex. The rocks of the anorthosite series are thought to represent original anorthosites, noritic anorthosites and troctolites, while the eclogite gabbros are thought to represent the gabbro facies of the original complex. The following sequence of events are postulated:

1. Emplacement of basic magma in Dharwar sediments during a period of quiescence, followed by fractional crystallization and gravitative differentiation resulting in a layered complex.
2. Chemical and mineralogical transformations of the various units of the complex, induced by the regional migmatization and metamorphism related to the formation of Peninsular gneisses. The anorthosites are amphibolized and the gabbros transformed to eclogites.
3. Elevation of the complex to present level of erosion with the accompanying retrograde changes of eclogites. Top of complex is eroded.
4. Forceful intrusion of the younger granite domes the complex resulting in its being tilted, dipping away from the center of intrusion. The mineralizers from the granite induced profound mineralogical transformations in the anorthositic rocks, resulting in the formation of clinozoisite, garnet and corundum, and the eclogites suffered further diaphoresis.

It is proposed to call this stratiform sheet 'Sittampundi Complex' after the village near its type exposure.

CHAPTER I

This Dissertation embodies the results of Petrological and Mineralogical studies on a group of basic rocks from the Archaean Complex of Southern India. The field studies, which form

INTRODUCTION

the basis of the laboratory investigations, were carried out on various occasions between the years 1944 and 1949, during the course of the writer's official duties with the Geological Survey of India. All the laboratory studies have been carried out in the Geology Department of the Princeton University, during the academic years 1949-50, and 1950-51, under the guidance of Professors H. H. Hess and A. F. Buddington.

These rocks occur in the Namakkal and Tirunchengodu Taluks* of the Salem District, in Madras State of the Indian Union. This area is

represented in portions of Survey of India Topographic

LOCATION

Sheets, 58 1/3, 1/4, E/15 and E/16, on the scale of 1 inch equal to a mile. The precise location of the area is between Latitudes 11°10' and 11°25'N and Longitudes 77°50' and 78°05'E.

The rocks from this area have figured in scientific literature nearly 150 years ago, in a classic paper by Count de Bournon (1802), who later proposed the name 'Indianite' for the calcic feldspar forming the matrix of corundum rocks. It is unfortunate that the law of priority did not apply to the name proposed by Count de Bournon, thereby denying this savant the credit of discovering and describing a most signi-

HISTORY OF PREVIOUS INVESTI- GATIONS

* Taluk, in Indian parlance, corresponds to a county.

ficant rock forming mineral. It may be of interest to mention in this connection that a specimen of rock, bearing this calcic feldspar, reached the United States one century ahead of the present writer, and has been described by Silliman (1849), accompanied by an analysis by Brush.

The first scientific report on these rocks appeared in the Philosophical Transactions of the Royal Society of London in the year 1802, by Count de Bournon and Richard Chenevix. Excerpts from the original paper by Bournon are quoted below, to indicate the excellence and completeness of his descriptions of rocks and minerals before the advent of mineralogy as an established science.

BOURNON
AND
CHENEVIX

Under the heading 'Matrix of imperfect corundum from the Peninsula of India, and chiefly from the Carnatic' Bournon's description runs as follows:

This matrix, which, as far as our present knowledge extends, appears to be peculiar to the imperfect corundum of this part of Asia, is a stone of particular nature: it is sometimes in masses of a loose and granulated texture, with very coarse grains, and pretty much resembles a coarse sandstone; at other times, it has a closer texture, the grains being nearer each other, and less distinct, so as either to give it an appearance similar to the kind of marble known by the name of 'Coarse-grained saline marble' or to that kind of prehnite which is composed of a mass of crystals confusedly aggregated. In this matrix, the crystals of imperfect corundum are dispersed, in the same manner as those of felspar are dispersed in porphyry, or rather in certain granites which, besides the aggregated constituent parts belonging to that kind of rock, also contain crystals of felspar which are of a more or less considerable size, and of a perfectly determined form.

When this substance is of that texture in which the grains are closely connected together, it is of a pearly grey colour, sometimes slightly tinged with green, and has a degree of semi-transparency, not unlike that of chalcedony. If a piece

of the kind is moved about in a strong light, its surface shows a considerable number of small brilliant particles. This appearance arises from the reflection of the light, by the small laminae that are exposed, in consequence of the fracture of the grains of which the stone consists; and this circumstance proves that it has a laminated texture.

The specific gravity of this stone, as determined by four trials, which scarcely differed from each other, was 2.742; but it is difficult to procure pieces of a tolerable size, which are not mixed, either with hornblende, or with particles of corundum. It is fusible by means of the blow-pipe.

This substance is more usually met with in pieces of a coarser texture, in which the grains are often pretty large, so as to be easily distinguishable by the naked eye. When these pieces are in a perfect state, the grains have exactly the same colour, and the same degree of semi-transparency, as those of the preceeding more compact kind. If examined with a lens, the laminated texture of these grains is very evident; and there seems to be, at the first view, a very distinct crystal in each of them. But if we endeavour to determine the form of any one of these crystals, we find that it is absolutely impossible to do so; as the greatest part of the small facets we perceive, are nothing more than facets formed by compression. I thought, indeed, that I could distinguish some traces that indicated an obtuse rhomboid; but not in such a manner as to permit me to state the fact with certainty. These grains have but a weak degree of adherence to each other; in consequence of which, the stone may often be broken by a very slight effort.

It is, however, still more common to meet with this substance in a state wherein it has undergone, at the surface of each of the grains of which it is composed, an incipient decomposition, that gives them a whiter colour, thereby obscuring, and indeed often destroying, that semi-transparency which I mentioned as being a character of this substance, in its two preceeding states. When this is the case, if some pieces of the stone are put into Nitric acid, an effervescence soon takes place, the strength of which is in proportion to the degree of decomposition the stone has undergone, but this effervescence, in a short time entirely ceases. It seems, from this circumstance that the lime contained in the stone, being exposed to the action of the air, by the alteration or decomposition of the stone, had afterwards combined with a portion of the carbonic acid.



View of ancient corundum workings on anorthosite band south of Sittampundi. Note barren nature of country devoid of vegetation.



Low hill of anorthosite north of Kattipalaiyam, towards N.E. end of complex.

To the above mentioned lime, ought no doubt to be attributed, that calcareous incrustation, which is frequently observed to cover either partially or entirely, many fragments of imperfect corundum, found among the specimens of that substance sent to us from India.

If we let a piece of this matrix remain for a certain time in nitric acid, it is attacked by it, without being dissolved, and without changing its form, but if after being taken out, it is pressed between the fingers it may be crumbled by a very trifling effort, by being rubbed be reduced to a sort of paste.

Count de Bournon (1817) in a subsequent description named the mineral 'Indianite', evidently in honor of the country from which it came.

The first field description of this area is by Captain Newbold (1843), who has described the occurrence of corundum in gneiss and a grayish earth, in great abundance, in a low hill near
 NEWBOLD,
 WARTH, AND
 MIDDLEMISS
 the village of Sholasigamany, Tiruchengodu Taluk. The next geologist to visit this area was Dr. Warth of the Geological Survey of India, in 1892, who made a report to the Government of Madras. The first published geological description of this area is by Middlemiss (1896), in a succinct account of the corundum occurrences in the Salem and Coimbatore districts, and his description is quoted below.

This locality lies a little east of the Cauveri river, and about five miles to the south of the boundary dividing the Tiruchengodu taluk from the Namakkal taluk. It has apparently been known for a long time. The size of the area productive in corundum was given by Dr. Warth as 771 acres, but the village officers gave 1000 acres as the estimated amount. It was also stated to be about four miles long and two miles broad in its widest part.

The part examined by me was about two miles long and varies in width from 100 yards to 1000 yards. It lies south west, and south east of Sittampundi village, occupying a slightly elevated bit of rising ground running with its long axis

west-north-west and east-south-east at distances varying, according to the position, of from 1 mile to 1/2 mile from the village.

The rocks to the north of the corundum area, consist of a great series of biotite gneissic rocks, covering large areas, and with bosses and veins of a coarse, reddish granite bursting through them and often forming picturesque crags and precipitous hills, such as that at Tiruchengodu town, and the similar hills in the vicinity.

But the actual rock present at the corundum workings differs from the above in being a gneiss or gneissic rock, of a pale silvery or pearly grey colour, streaked with black, and consisting of anorthite (Indianite) and hornblende chiefly, with accessory minerals, garnet, and minute quantities of chondrodite (?). In structure the rock is a crystalline granular aggregate of anorthite with rather elongated prisms of hornblende, sparsely or numerous arranged with their longer axes roughly parallel to the foliation.

The rock is well foliated in bands which generally run perfectly straight and which differ in the relative amounts of the pale mineral (anorthite) and the dark mineral (hornblende) present.

In some places the hornblende, in others the anorthite, make up nearly the whole rock. Garnets also become locally very numerous. The specific gravity of a specimen with but little hornblende and garnet was found to be 2,824. In this respect it closely resembles anorthite, the specific gravity being a little higher than that of the latter on account of the hornblende.

It is among this gneiss that the corundum appears, dotted about at random among it like porphyritic crystals of orthoclase in a granite. The mineralogical composition, structure and general appearance of the rock-matrix here is plainly the same as that recorded by Count de Bournon from the Salem district, and named 'Indianite' by him. The microscopical examination of the two rocks shows them to be practically identical.

On each side of the in-situ gneiss, which forms the rising ground, there are gentle slopes of the same rocks, partly or wholly buried under surface material formed of the broken up gneiss and with here and there a recent calcareous pisolitic tufa, derived no doubt from the decomposition of the lime felspar (anorthite).

The corundum occurs in two ways in the area:-

- (1) In the bed rocks as described above
- (2) In the gentle slopes of debris along with the weathered pieces of the bed rock.

It is of a pale greenish-gray, rarely flesh colour, and occurs sparsely distributed among the parts of the gneiss which are richer in anorthite. It takes the form of irregular lumps averaging from one-fourth to one inch in diameter. They do not, as a rule, show the prismatic and pyramidal faces, though some specimens from this locality in the Survey Museum are in the form of short six sided prisms characteristic of corundum. Nearly all these pieces of the mineral are surrounded by a shell of calcite from one-fourth to one-eighth inch thick, in which they lie among the matrix. The shell appears to be left by the crystallising out of the alumina (corundum) from the lime bearing felspar (anorthite).

The corundum found in the debris slopes is the same as that of the matrix rock inasmuch as the former is simply derived from the latter by weathering.

Besides the grey corundum noted above, and the flesh coloured variety into which it passes, there are to be found fragments generally minute of red corundum which very locally passes into ruby. The brighter coloured pieces of these, which are but seldom larger than one-fourth of an inch in diameter, were found by me only in the more hornblendic layers of the gneiss; and they lie in it surrounded by a shell of anorthite partly converted into calcite. These pieces are not generally transparent, but dull and opaque, and of a red currant colour. But here and there minute points of a fairly translucent red colour may be detected, and I have no doubt that occasionally rubies of value have been extracted from these rocks as reported traditionally, and by Newbold (1843).

The most important contribution to the petrography and mineralogy of these rocks is contained in a monograph by Lacroix (1889), entitled

'Contributions a l'etude des gneiss a pyroxene et des
LACROIX

roches a wernerite', relevant sections of which have been translated by Mallet (1891). This monograph by Lacroix is based on his petrographic and mineralogic studies of several collections of rocks from India and Ceylon, including those of Count de Bournon, preserved in

the French Museum of Natural History. It must be stated here that the scientific value of this excellent paper has been somewhat diminished by the lack of precise information on the localities of occurrence of the rocks described, probably due to bad cataloging of the original collections on which he based his work. Lacroix' paper contains chemical analyses of indianite, and thallite (Clino-zoisite), besides a wealth of optical data on the various minerals, and detailed petrographic descriptions of the various rocks. He has considered Bournon's thallite to be a new mineral and called it 'Fouqueite'.

In 1933, Iyer, of the Geological Survey of India, presented a brief paper on these rocks at the Indian Science Congress, and which has not, however, been published in full. According to Iyer, these rocks have resulted by the "differentiation fractionation of a basic magma, which has given rise to the large exposure of anorthite gneiss, in which the ultrabasic fraction consisting of chromite-pyroxene rock, and basic garnet plagioclase pyroxene rock, is intrusive". The pegmatites and quartz veins in the area are considered by him to be the acid fraction of the same magma. He also postulates an oversaturation of the anorthosite fraction of the magma in alumina which subsequently crystallized out as corundum.

During World War II the increasing demand for corundum resulted in a revival of mining and prospecting activity in this area. Early in 1944, the writer accompanied Aiyengar, of the Geological Survey of India, to re-examine the corundum area, to assess the prospects of corundum production. The few traverses in the area resulted in the discovery of seams of chromitite within the anorthosites, extending for

several miles, and it was soon realized that the true extent of these basic complex rocks had not been realized by the geologists who had previously visited this area. A couple of weeks were spent in mapping the chromite rich horizons in the field. As the chemical analyses of several samples of chromite ores and concentrates indicated them to be of inferior grade, interest in the area was lost. However, Aiyengar traced the eastern and north-eastern extension of this belt of rocks during the course of his systematic mapping of the region in the succeeding year. In the meanwhile, the writer was able to make a brief petrographic study of these rocks and realize their uniqueness, but other duties in the Geological Survey prevented further work on the rocks. Early in 1948, the writer had an opportunity to revisit the area and collect bulk samples of chromite ore, for experimental work. This opportunity was used to make a detailed field study of the rocks. The original geological map of the area was carefully revised and collections of all the rock types in the area were made from critical sections. In the Fall of 1949, the writer was permitted by Government to proceed to Princeton University to study these rocks, and another brief visit was made to the area prior to leaving India. On the whole about 5 weeks were spent in the field study of the rocks.

The present investigation has concentrated on the mineralogy, and petrography, of these rocks, their probable mechanism of emplacement, the history of their metamorphic and mineralogical transformations, and the origin of the chromite and corundum; in order to throw some light on their genesis. Over 400 thin sections were examined, and the optical properties of a large number of minerals

PRESENT
STUDY

in them determined. The interpretations in this paper are based on these results together with the chemical analyses of 7 rocks and 10 minerals. It must be stated here, that this study cannot be considered complete, and the inferences arrived herein, will require the writer to make more comprehensive field studies of the complex, and supplement these with further laboratory work. It is hoped that future work will throw greater light on many of the problems raised.

CHAPTER II

A brief review of the geology of the Archaean complex of Southern India, would help in a proper appreciation of the local geology of the area under consideration. Pascoe (1950) has revived the old correlations of the Indian shield with the Canadian shield, with modifications in the light of more recent work, as shown below:

CANADA		SOUTH INDIA	
Algoman granites		Bellary or Closepet granite	
Huronian	)	(	Charnockite suite,
	)	(	Peninsular gneisses,
Timiskaming	)	(	? Champion gneiss
Ontarian	(	Keewatin	Upper Dharwar
	(	Grenville includ-	Lower Dharwar.
	(	ing Couthiching	

In Southern India, the Mysore region has received attention from geologists for over a century, and the most recent account of the stratigraphy and petrology of this region is by Rama Rao (1940). The stratigraphic succession of the several rock formations in the Archaean complex of the Mysore region, as deciphered by Rama Rao, and their correlation with the Archaean rocks of the Madras region by Krishnan (1949), are:

MYSORE	MADRAS
Closepet Granite	Bellary, Hosur, Arcot and other granites
Charnockite	Charnockite
Peninsular gneiss	Peninsular Gneiss
Upper Dharwar (Clays, silts, grits etc.)	?
Middle Dharwar (Banded ferruginous rocks, quartzites etc.)	Magnetite and haematite quartz schist etc.
Lower Dharwar (Chloritic, hornblendic and micaceous schist etc.)	Chloritic schist etc.

MYSORE

		<u>Original Formations</u>		<u>Probable Alterations</u>
Pre-Cambrian		11	Basic dykes-chiefly dolerites	
Eparchaeon Unconformity		10	Felsites and porphyry dykes	
		9	Closepet granite	Slightly foliated
A		Recrystallization and reconstruction of older rocks into complex types of the Charnockite series.		
		8	Norite dykes	
R		7	Hornblendic dykes	Slightly crushed and granulitic
C			Peninsular gneiss	Complex granitic gneisses
H Eruptive Unconformity		6	Some ferruginous and cherty silts, clays, calcareous silts and clays, impure quartzites and conglomerates forming in part the G.R. Formation. (Local)	Somewhat altered, Otherwise easily recognizable.
A		U		
		P		
		P		
		E		
E D		R		
		5	Granite porphyry and granitic rocks, fine and coarse.	Micaceous granitic gneisses and crushed foliated gneissic granites.
A H				
		A		
N R				
		4	Basic and ultrabasic intrusives	
		M		
		I		
G A		D	3 Ironstones, limestones, argillites, quartzites and conglomerates; also ashes, tuffs and other volcanic products.	Banded ironstones, with amphiboles, etc., granular crystalline limestones, micaceous gneisses with cordierite, sillimanite quartzites, schistose conglomerates, all highly crushed and crystalline.
		D		
R R		L		
		E		
O S				
		Y		
U S				
		T		
P E		2	Rhyolites, Felsites and quartz porphyry and other acid volcanic rocks with opalescent quartz.	Quartz schists, micaceous quartz schists and gneisses with opalescent quartz, highly crushed.
		L		
		O		
		W		
		E		
M R				
		1	Basic volcanic flows and dykes.	Greenstones, hornblende schists, etc.

Original basement not recognized.

The above statements of Archaean succession in Southern India gives a fairly clear picture of the stratigraphic position and lithology of the various units constituting the Archaean Complex. Brief descriptions of the major units, in the Archaean, follow:

The Dharwar formation which takes its name after the district of its type occurrence, consists of an assemblage of crystalline schists, meta-volcanics, meta-sediments, basic and ultra-basic DHARWAR SYSTEM intrusives, and intrusive masses of porphyry. The origin of this group of rocks has been one of the major controversies in Indian Geology, some advocating a wholly igneous origin and others a wholly sedimentary origin. The most recent contribution to the geology of these rocks is by Rama Rao (1940) who states:

The Dharwar system forms a complex composed of igneous volcanic rocks, deformed rocks of sedimentary origin, and crystalline schists derived from intense alterations of the one or the other. There are also some types which belong to neither of three categories. They form a class by themselves, and have originated from the intermingling, in different proportions, of both igneous and sedimentary material. In addition to all these the system also contains some basic, ultrabasic and other intrusive rocks.

The following observation by Pascoe (1950) is pertinent with regard to the ultrabasic intrusions in the Archaean:

The precise age of the ultrabasic amphibolites, pyroxenites, peridotites, amphibole peridotites, talc schists, talc chlorite schists and dunites of Mysore and other parts of India is not always certain. It has been suggested that some of them, especially those occurring isolated in the Peninsular gneiss belong to the later intrusion known as the 'Charnockite' suite. Whether this is so or not, the intercalation of grey amphibolites, more or less conformably among the hornblende schists of the Dharwars and their truncation and fracture by the subsequently intruded Peninsular granite, are more in favour of the Dharwar age of these particular examples, though they may well have been intrusive towards the older schists

among which they occur. The amphibolites consisting entirely of amphibole (which is commonly hornblende, but often actinolite or tremolite), are sometimes coarse in grain. Most of them are found in the Hornblendic division and appear to represent sills, dykes and laccolites in the mass of the schists. It has been suggested that some of the quartz iron rocks have been derived from them. Corundum is frequently developed in the amphibolites, along their contact with the gneiss, but here again, the precise age of the mineral and rocks is not known and these occurrences will be described later on. The alteration products are mostly serpentine, potstone, and magnesite.

In a recent note, Pichamuthu (1951) has postulated an anticlinorial structure to the Dharwar rocks of Mysore, and suggests that the belt of ultramafic rocks of that region have probably been emplaced along the axial plane of this major fold.

This is the prevalent rock type in a vast area of the Peninsular ~~terrane~~, and regarded by some authorities as the basement on which the Dharwarian sediments were laid. This view has been rejected by workers in the type area, where no base has been so far revealed and unequivocal field evidence has been presented indicating the intrusive nature of these gneisses into the Dharwarian rocks. The views of the Mysore workers have to be extended to the whole of Southern India, in the absence of any detailed field data in the latter region.

Rama Rao (1940) has included under the Peninsular gneissic complex, the following rock types, (i) banded gneisses, (ii) granitic gneisses, (iii) gneissic granites, (iv) granites, granodiorites, inter-action diorites, and other variants, and considers some of them to be a result of replacement.

It is difficult to visualize any single process to explain the mechanics of emplacement of this vast terrane of Peninsular gneiss, particularly in view of the fact that many of the primary structures have been obscured by the intrusion of the younger pink granite. Smeeth (1911) regarded them as thick horizontal sheets emplaced within the Dharwar schists. The writer would be inclined to regard the Peninsular gneiss complex to be the result of the remelting of the Upper Dharwars and emplacement by a process similar to that advocated by Wegmann (1935), marking the cessation of post-Dharwar orogeny. Dunn (1942) has also postulated a similar view, adducing, remelting, rheomorphism and hybridization of the older schists.

The most important group of rocks in the Archaean of the Peninsula, are the so-called charnockites. Unfortunately, the original terminology proposed by Holland (1900) has been indiscriminately extended to rocks formed by processes different from that ascribed to the original charnockite not only in India but all over the world. Rama Rao (1945) has presented his observations on the charnockites of Mysore, studied by him for over twenty-five years. According to this authority, the charnockites of the Mysore region have resulted from a number of petrogenetic processes, (i) repeated metamorphism of impure sediments, (ii) crystallization differentiation of contaminated sheets, (iii) reaction of alkaline fluids and subsequent, incorporation assimilation etc. In ascribing the above processes to explain the origin of the charnockites, these rocks lose their stratigraphic significance as well, and would range in age from Dharwarian to the Younger granite periods. It appears to the writer that there has

been an unfortunate grouping of altogether unrelated rocks, under the name charnockite, but it is hoped that future work in the Peninsula will delimit the areas of true charnockite. The rocks of the charnockite series vary from ultramafic types to acid granites with hypersthene as a common constituent, and texturally range from schistose granulites to coarse porphyritic types. The charnockites are thought to have penetrated the Peninsular gneiss complex in the form of intrusive tongues, which transgress the foliation of the older gneisses. This transgression, according to Pascoe (1950), is not a simple injection, but more of the nature of a corrosion, on the basis of the presence of imperfect pseudomorphs of old gneissic structure in the corroding charnockite magma. He also suggests an intermediate age between the Peninsular gneiss and the younger granite, for the charnockites, in view of their lacking any visible signs of tangential compression. Holland (1900) writes:

Foliation of the Charnockite series is much less pronounced, than that of the accompanying gneisses and schists, and is sometimes practically absent, especially in the central portions of large masses, whilst the 'banding' is generally a mere streakiness of aspect due to deformation of a 'Schlierig' mass, and not due, as in the schists, to continuous bands of dissimilar aggregates.

A series of dykes and thin lenses of basic norites and pyroxenites intrusive into the acid charnockite massifs, Peninsular gneisses and the older schists, are believed to represent the final phase of differentiation of the charnockite magma. More recently, Rode (1948) has postulated a universal origin for the charnockites all over the world, relating their formation to a Pre-Cambrian orogeny accompanied by a hornblende magma, and states:

The charnockitic suite of rocks is not restricted to any particular petrographic province of limited areal extent but like the circum-Pacific suite will be found developed in all the regions of the world which have suffered similar earth-movements.

The last phase of widespread igneous activity in the Pre-Cambrian of Southern India is the intrusion of granites of batholithic dimensions, which have soaked and permeated through the older rocks.

YOUNGER GRANITE

These granites have been described under various local names such as Pink granite, Closepet granite, Arcot gneiss, and Bellary gneiss, and Fermor (1940) suggested the last as a suitable type name for all these younger granites of Southern India.

These rocks are coarse grained, porphyritic, gray to pink biotite granites, the color being due to the predominant potash feldspar. Massifs of these granites are structureless in the center, though occasionally displaying flow banding along the intrusive margins, and carry inclusions of all older rocks of the region. According to Rama Rao (1940) these rocks are differentiates of a contaminated potash granite magma, and he considers the dioritic and tonalitic inclusions in the granites to be granitized inclusions of older rocks. These younger granitic rocks are of widespread distribution in the Madras region, and as stated earlier obscured the relationship of the Peninsular gneisses to the Dharwars. Pegmatites and quartz veins related to this granite are found all over the Peninsula.

The Peninsula is a comparatively stable block and has not suffered any marked movements since pre-cambrian times, except for some faulting in the Mesozoic. The Archaean basement on which the post-cambrian rocks are laid is highly folded and sometimes overthrust. Krishnan (1943) has

deciphered certain regional trends in the Archaean which he believes to be coincident with the major fold axes, and offered some tentative suggestions, correlating these trend lines with compressive movements suffered by the Indian Peninsula.

Fermor (1936) has proposed an arbitrary division of the Archaean complex into two main regions, the Charnockitic and the Non-charnockitic, subdividing his regions into provinces and types.

STRUCTURE OF THE ARCHAEOANS

According to this scheme, our area falls under the Iron-ore province of the Charnockitic region constituting the Salem type.

Orographically the Charnockitic region, though largely made up of plutonic rocks, is on the whole at a higher level than the Non-charnockitic region, suggestive of a relative uplift of several thousands of feet. Fermor postulates that this uplift must have taken place after the isogeotherms in the earth's crust had fallen sufficiently in the Charnockitic region prior to fall of pressure to permit the rocks to preserve their hypo-metamorphic characters, though raised to levels of lower pressure. He also states that there has not been a general application of stress during uplift.

As to the mechanism of uplift, Fermor has two suggestions, (i) general tilt to the Peninsula producing relative uplift of the south-eastern end with relative depression of the north-western end, and (ii) elevation of the Charnockitic region through vertical uplift along structurally weak zones, postulated along the boundary of the Non-charnockitic and Charnockitic regions. Recently Charnockitic rocks have been found in Fermor's Non-charnockitic province, and for the time being his concepts have to be accepted with reservations.

GEOLOGY OF THE ANORTHOSITE-ECLOGITE GABBRO COMPLEX

The Salem district forms one of Fermor's type sub-divisions of the Iron-ore province of the Charnockitic region, and the general succession of rocks is as indicated on page 10. The following general sequence was established by the writer in the area of occurrence of the basic complex, to be described in this paper.

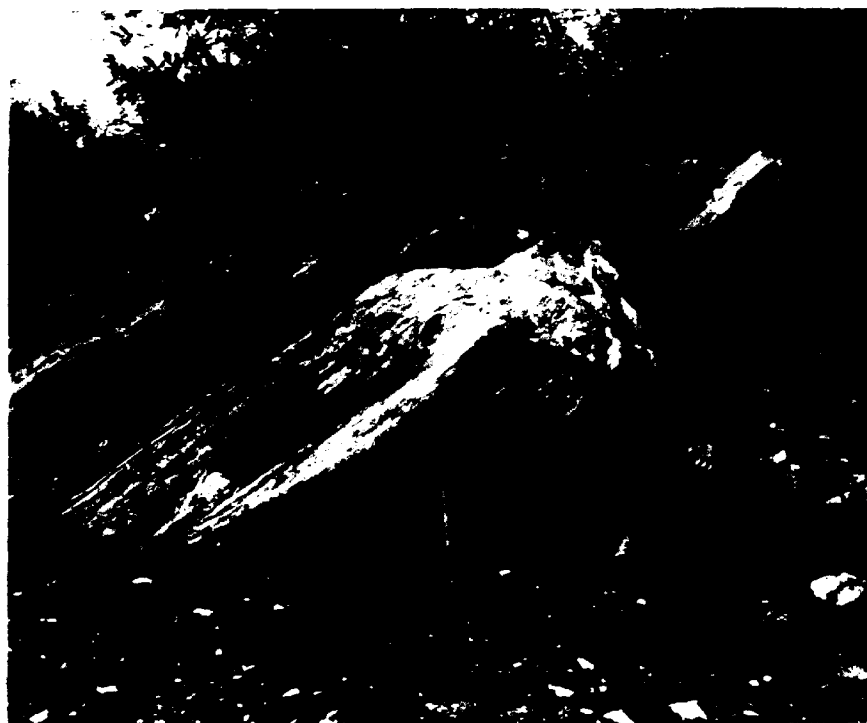
STRATIGRAPHIC POSITION	ROCKS OF THE AREA
Closepet or Arcot granite	Pink granites and pegmatites
Charnockite	Pyroxenite-websterite
Peninsular gneiss	Biotite gneiss and migmatites
Upper Dharwar (?)	(Anorthosite-Eclogite gabbro Complex
Dharwar	(Ultra-basics-peridotites, (saxonites and dunites; Banded (magnetite quartzite, crystalline (limestone, amphibolites and (hornblende schists

The Anorthosite-eclogite gabbro complex consists of an assemblage of anorthosites with interbedded chromitite seams, and a group of eclogite gabbros, occurring as an arcuate belt, among the Peninsular gneisses, with a lateral extension of nearly 25 miles and a maximum width of nearly 7000 feet.

At its western end the belt has a nearly east-west direction of strike, and steep southerly dips of over 70° . Proceeding eastwards the rocks veer to an east-southeasterly trend, straightening out again about five miles farther. The complex attains its maximum width south of Sittampundi. From here on the belt thins out gradually, at the same time veering to an east-northeasterly trend, straightening out again about



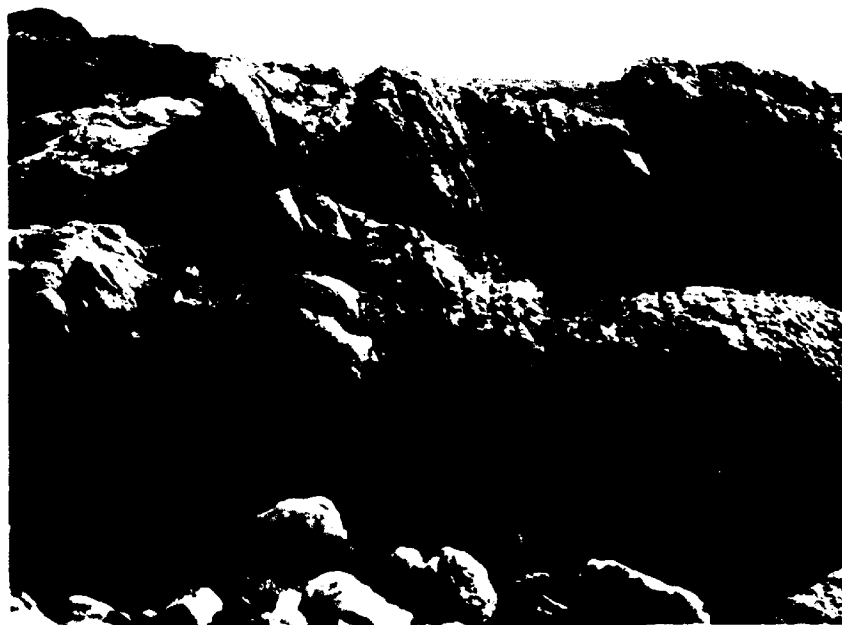
Steeply dipping anorthosite, our crop near Pamandapalaiyam.



Anorthosite outcrop east of Kattupalaiyam, note lower dip of rocks.



Foliated amphibolite on northern margin of complex, south of Konasamudram.



Typical exposure of steeply dipping, weathered anorthosite. Exposure on high ground south of Sittampundi.

five miles farther in the vicinity of Karungalpatti. The dips all along are at steep angles to the south. From Karungalpatti this belt of rocks takes a sharp northerly trend, in the form of an arc, ending up 7 miles to the north near Suryapatti. Between Karungalpatti and Suryapatti the anorthositic rocks form individual bands of varying thickness, forming a number of small ridges, and hillocks, which are conspicuous by their absence in the western section of the belt. The dips are also relatively low in this section, varying from 25° to 60° .

The major rock types of the area recognizable in the field are: (i) anorthositic gneisses and their variants, (ii) chromitite layers within the anorthosites, (iii) eclogite gabbros consisting of garnet pyroxenites and garnet amphibolites, (iv) pyroxenite-websterite, (v) amphibolites, (vi) biotite gneiss, and (vii) pink granites and related pegmatites, the first three types representing genetic units of the basic complex. The general distribution of these rocks are shown in the petrological map, accompanying this paper.

The complex as a whole is largely composed of anorthositic rocks containing variable proportion of ferromagnesian minerals and corundum, extending as an arcuate belt. The chromitites are confined to the anorthositic rocks, occurring as seams of variable thickness, without any transgressive relationship to them. The alternation of salic and mafic bands of anorthosites, and the remarkable persistence of chromitite bands within them, bear an unmistakable similarity to the Dwars River section in the Bushveld Igneous Complex of South Africa. At other localities in the Bushveld, however, the occurrence of chromitite within the anorthosite is exceptional according to Kupferburger (1937).

The eclogitic rocks consisting of a variety of garnet pyroxenites and garnet plagioclase amphibolites, occur as discontinuous bands within the anorthosites, and as fairly consistent bands outside them. They form low ridges and small knolls in the area, due to their being more resistant to weathering than the anorthosites. These eclogitic bands are structurally conformable to the anorthosite bands, as they maintain the same strike and dip directions as the adjacent anorthosites. Peridotites occur a mile south of the main anorthosite band, as a series of lenticular masses in the gneisses, and are apparently genetically related to the larger masses of peridotites in the district. The rocks comprising these are mainly dunites, hornblende peridotites, and pyroxenites. The dunites have been altered in many places to magnesite, forming a network of economically workable veins. Small masses of pyroxenite (websterite) which appear to be intrusive into the anorthosite complex, occur at four places. Their freshness, and lack of any mineralogical and textural transformation comparable in magnitude with those of the anorthosite complex, also point to their being a later intrusion.

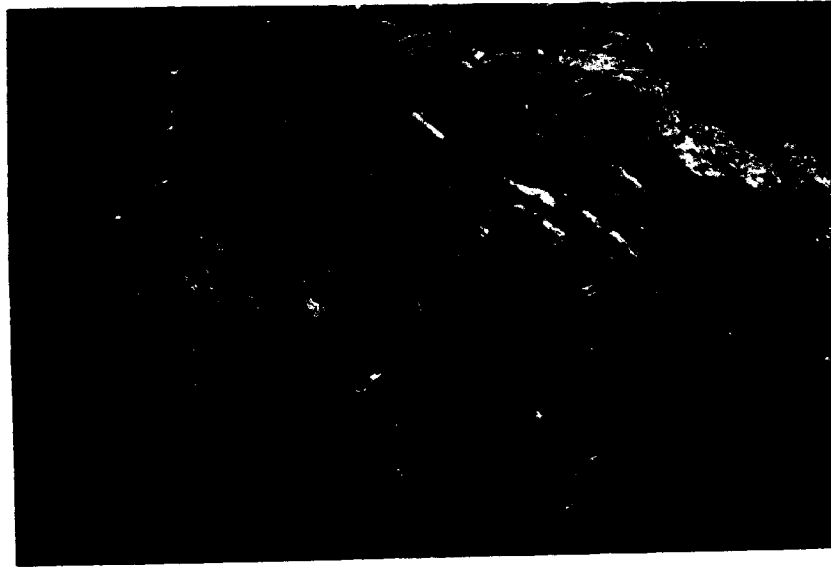
Amphibolites are found in close association with the anorthosite complex forming a definite zone particularly along the northern margin, conformable with the anorthosites. They appear in the southern margin of the complex also grading into biotite gneisses. It is thought that these amphibolites are members of the meta-sedimentary floor on which the basic complex was emplaced, but the possibility of their being igneous and genetically related to the complex cannot be ruled out. The southern portion of the area is predominantly gneissic, consisting of migmatized biotite gneisses with interlayered crystalline limestone and calciphyre.



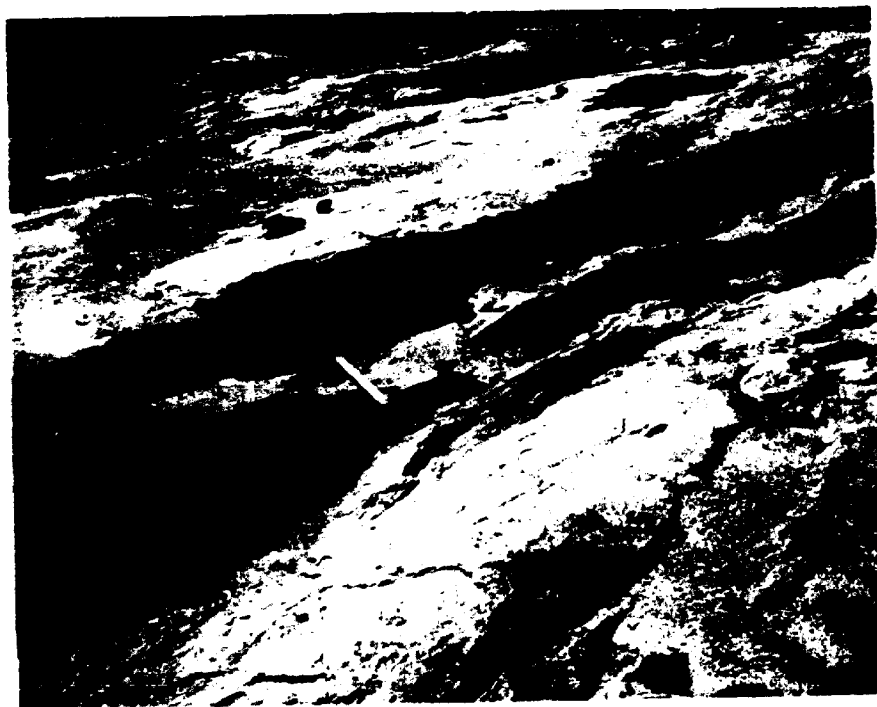
Typical exposure of anorthosite with mafic bands, on high ground south of Sittampundi. The dip of foliation is almost vertical.



Outcrop of eclogite gabbro near Gangarapalaiyam, note visible foliation.



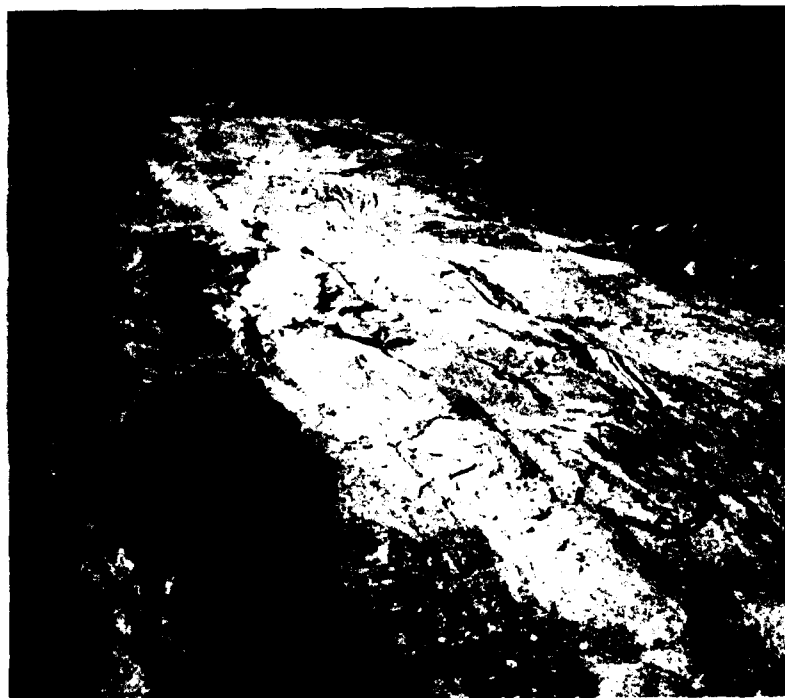
Anorthosite with mafic layers, outcrop near Molasi on western end of complex.



Large band of hornblende rock in anorthosite, outcrop near Sanarpalaiyam.



Banded anorthosite, outcrop near Sayakkadupudur. Is it flow banding or secondary banding induced by metamorphic differentiation ?



Offsetting of hornblendic band(?) in anorthosite, outcrop near Mannadipalaiyam.

The later intrusions have transformed some of the older gneisses into injection gneisses. Pink granite and related pegmatites are conspicuously developed on the northern portion of the area, and as will be shown later have forcefully domed the entire region, outcropping as bosses and stocks, over much of the area.

STRUCTURE

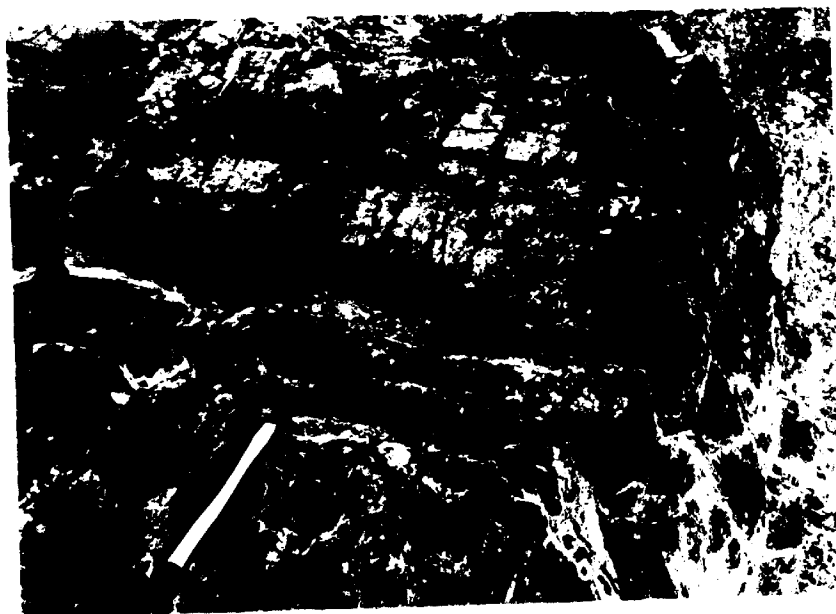
The close association of anorthosites with included seams of chromite, and gabbroic rocks, is very similar to that obtaining in several basic complexes, occurring in other parts of the world. The conformity of structure between the various rocks forming the complex, and the layered character of the anorthosites and associated chromitites, point to the present complex being a gravity stratified sheet. Further evidence on the basis of the petrography, mineralogy and chemistry of these rocks will be presented in a later section of this paper to support this concept. The anorthosites as already mentioned, contain within them several mafic bands wholly composed of hornblende, and, in general, the rocks contain a variable proportion of this mineral. The hornblende crystals are aligned with their longer axes in the plane of the banding, imparting a planar structure, apparent in hand specimens of this variety of anorthosite. The prismatic crystals of hornblende display a fairly consistent parallelism to one another in the plane of foliation, resulting in a distinct horizontal lineation. The epidote-clinozoisite group of rocks occurring in some of these rocks also display a parallelism similar to the hornblendes, but the corundum crystals present in them, as far as noticeable, grow with their c axis across the lineation. The chromitites also display a linear structure conformable to that in the anorthosites



Pseudo-boudinage structure of mafic bands in anorthosite, outcrop north of Kattipalaiyam.



Seam of chromitite exposed in old corundum quarry at Karungalpatti.



Jointing in chromitite, exposure at Karungalpatti quarry.



Jointing in anorthosite, old corundum quarry south of Sittampundi.



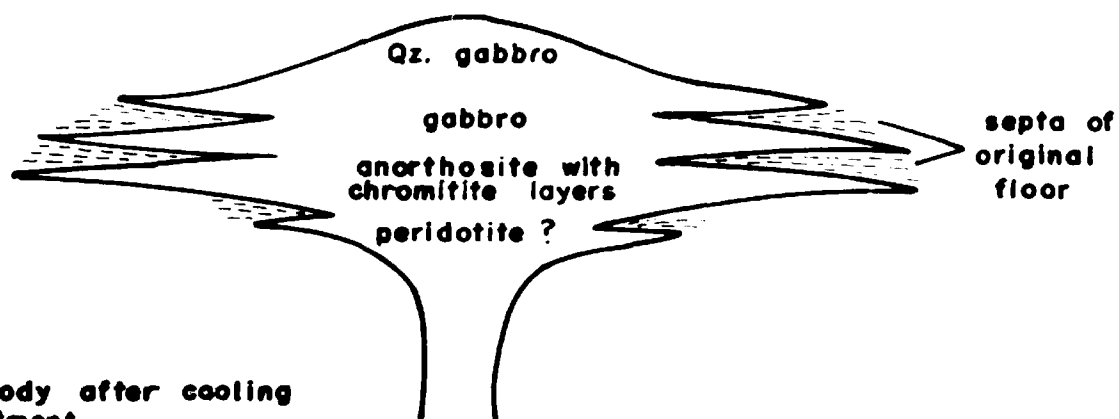
Jointing in anorthosite, outcrop at Kottakkaradu, east of Karungalpatti.

enclosing them. The lineation in the rocks of the basic complex is parallel to the lineation in the adjacent amphibolites.

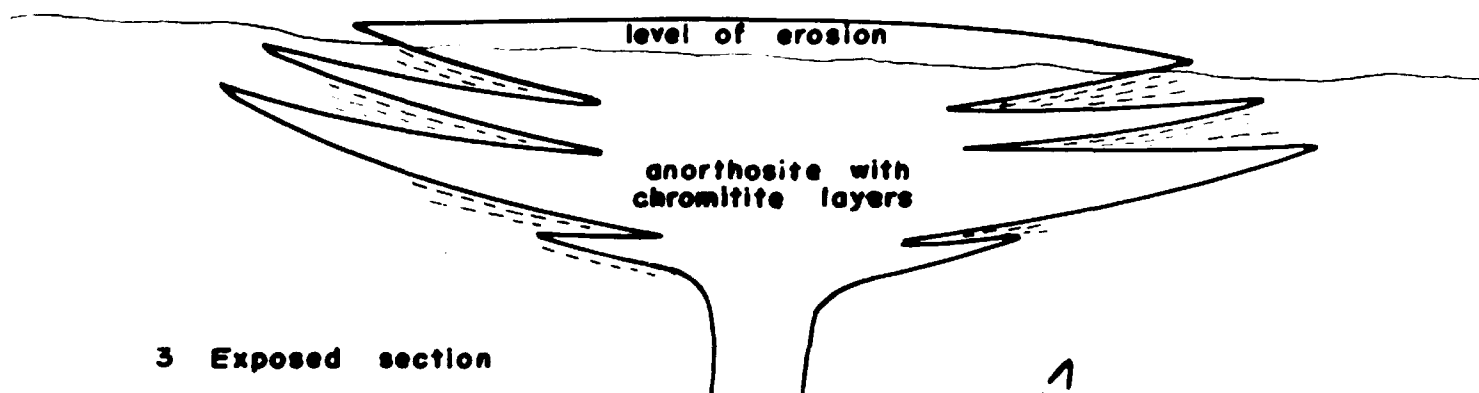
A system of vertical and horizontal joints is seen in the rocks constituting the complex, particularly in the chromitites and anorthosites, and to a lesser degree in the eclogitic gabbros. Towards the north-eastern of the complex the anorthosites contain several mafic bands and many of them simulate flow banding or schlieren banding, and at one point these were noted to have a 'Boudinage' structure.

The anorthosites and eclogite gabbros forming this belt have an arcuate disposition with steep southerly or easterly dips according to the prevailing strike. It is difficult to interpret the relative position of these two types, particularly in view of the metamorphic transformations undergone by them. However, by general comparison with other gravity stratified sheets, we may consider the anorthosites and related chromitites to represent the bottom and the eclogitic gabbros the top of gravity stratified sheet. It is conceivable that what is exposed now is only a certain section of the complex, the remaining sections in the bottom being concealed, and the upper horizons being eroded off. With this assumption it would be possible to reconstruct a probable sequence of events with regard to our complex. It is postulated that a basaltic magma was emplaced in the form of a sheet in gently folded Dharwarian meta-sediments, as in figure 1, assuming a general form as in figure 2, after cooling and adjustment. This must have taken place during a quiescent period, following the post-Dharwar orogeny, as evidenced by the uniform distribution, and lateral extent of the chromitite seams within the anorthosites. After a considerable length of time, during

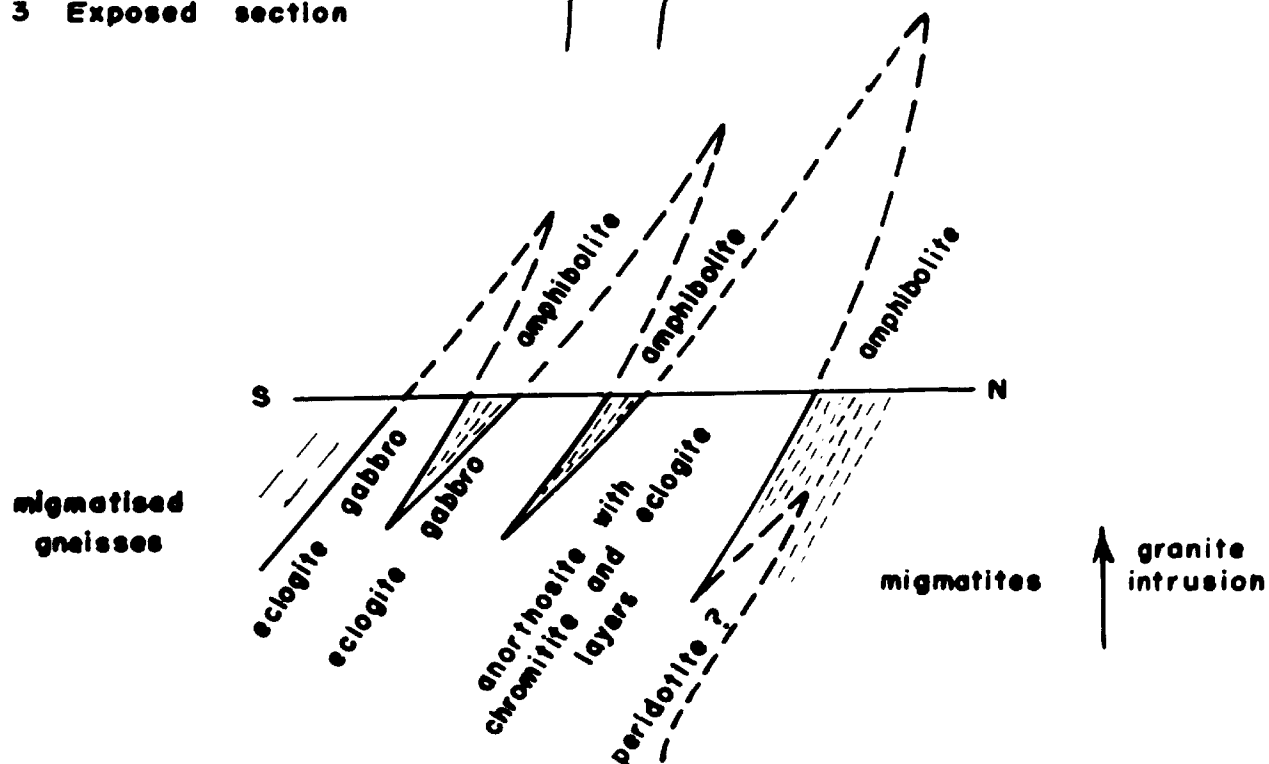
1 Hypothetical form of original intrusion



2 Form of body after cooling and adjustment



3 Exposed section



which the crystallization and settling of the crystals must have been accomplished, the level of erosion reached the complex, and probably at the same time cut the charnockites. A considerable period of time must have elapsed before the next major event took place, during which the top sections of the complex were eroded off. The younger granite intrusion, represented in the area by Pink granites, is thought to have domed up the older rocks of the area, during forceful intrusion, with the result that the anorthosite complex was tilted to its present position as in figure 3, actually representing a remnant of ancient rocks on the southern margin of a large dome, the center of which is located about ten miles to the north and represented by a large granite massif. The above interpretation has been adopted as a working hypothesis, and in a concluding section will be re-examined in the light of petrographic, mineralogical, and chemical data. It is suggested here that this complex be called SITTAMPUNDI COMPLEX after the village of its type exposure.

CHAPTER III

The mineralogy of the rocks comprising the Anorthosite-Gabbro complex is of significance in interpreting its genetic and metamorphic

history, and some of the following minerals have been
INTRODUCTION studied in some detail, chemically and optically.

Oxides

Type $A_2 X_2$ Corundum
Type A X_2 Rutile
Type A $B_2 X_4$ Chromite, Spinel

Silicates

<u>Group</u>	<u>Manner of Linkage of Silicon-Oxygen Tetrahedra</u>	<u>Minerals</u>
Neosilicates	Separate (SiO_4) islands which do not share any oxygen with the neighboring SiO_4 tetrahedra.	Garnets, Spinel
Sorosilicates	Rings of six tetrahedra.	Cordierite
Inosilicates	Infinite chains or double chains of SiO_4 tetrahedra	Epidote- Clinzoisite Amphiboles Pyroxenes Sillimanite
Tectosilicates	Continuous frameworks of linked tetrahedra, sharing all four oxygen atoms with neighboring tetrahedra.	Plagioclases

To ensure purity of the mineral specimens used for chemical analyses, careful separations were made, using the Frantz Isodynamic Magnetic

SEPARATIONS Separator, heavy liquids and the centrifuge. A brief description of the methods of separation of the various analyzed minerals follows.

Garnets: Two garnets from the meta-gabbros and one from the anorthosite were separated for chemical analysis. The rocks were crushed to pass through a 40 mesh sieve, and a measure of separation effected by sifting the material. This material was then crushed to pass through 80 mesh sieve and the fines removed by sieving through 120 mesh sieve. Iron filings from the mortar and magnetite grains, present in the above material, were removed with a bar magnet before introducing the same into the magnetic separator. By varying the field strength and angular tilts of the magnetic separator for repeated runs of the material, almost pure garnet was separated from the rock. Heavy liquid separation using tetrabrom-ethane was resorted to for eliminating feldspar grains, and repeated several times to ensure purity. This concentrate was once again run through the magnetic separator at a slightly higher field strength to eliminate any compound grains of garnet and pyriboles, and the final concentrate washed free of traces of heavy liquid.

Amphiboles: Essentially the same procedure as above was adopted to separate the amphiboles. The separation of ortho-amphibole from clino-amphibole was easily effected by varying the field strength of the magnet.

Cordierite: Fragments of cordierite were hand picked from coarsely crushed rock and reduced to 100 mesh size. After eliminating the iron filings with a bar magnet, and the fines by sieving through a 120 mesh, the material was run through the magnetic separator with varying field strengths to eliminate anthophyllite, sillimanite, anorthite and corundum. This concentrate, on microscopic examination, was found to contain compound corundum-cordierite grains and an abundance of cordierite grains

with inclusions of sillimanite. Heavy liquid separations were repeated several times using tetrabrom-ethane of varying density. The final concentrate was again run through the magnetic separator to eliminate stray grains of feldspar.

Clinozoisite: Separation was easily effected by running the material through the magnetic separator after reducing to 80 mesh size. Compound grains of the mineral with corundum and anorthite were eliminated by heavy liquid separations using liquids of varying density.

Anorthite: The rock containing anorthite, clinozoisite and corundum was reduced to 80 mesh size and the fines removed by sieving. Most of the corundum was eliminated at this stage due to its failure to crush to an even size with feldspar. The material was then passed several times through the magnetic separator to eliminate clinozoisite grains. Next, the material was reduced to 100 mesh size and run through the magnetic separator repeatedly, after eliminating the fines. Heavy liquid separation was resorted to for removing the compound grains of anorthite with corundum or clinozoisite. This final concentrate though composed wholly of anorthite, was found on microscopic examination to contain a fair amount of kaolinized grains. The material was run in a centrifuge at 2000 r.p.m., using a heavy liquid close to that of anorthite, resulting in an excellent separation of pure anorthite free of alteration. The final concentrate was washed in dilute acetic acid to remove traces of carbonate, and then washed several times in distilled hot water.

Chromite: The ore was reduced to 100 mesh size and run through the magnetic separator several times, eliminating the amphiboles, corundum,

and rutile. The material was then reduced to 120 mesh size and heavy liquid separation was made using methylene iodide, to float all the silicates. This was repeated twice and the final concentrate run several times through the magnetic separator at low field strengths to eliminate stray grains of silicates and other non-magnetic minerals. It may be stated here that the quality of the material used in several chemical analyses in the literature, is not beyond question as most of them were made before the advent of the Frantz Isodynamic Magnetic Separator. The potentialities of this instrument as an essential tool for mineral separations have been fully brought out during the course of the above work involving the separation of a variety of silicates. The separation of cordierite, which is generally known to contain inclusions of sillimanite, staurolite, spinel, etc., and alter to pinite, can be taken as a specific case. Most of the analyses of this mineral in the literature do not contain any information on the quality of the material used. In the present instance, separation was done at 100 mesh size using the magnetic separator and heavy liquids, thus ensuring complete elimination of any other mineral. It is doubtful if many of the analyses of this mineral in the literature have been made on pure material.

OPTICAL PROPERTIES

Indices of refraction: The principal indices of refraction of the minerals were determined by immersion methods using closely spaced and calibrated liquids, and using a temperature-controlled cell in the case of analyzed material. The determinations have been made in sodium light, and the accuracy of the determinations made with a temperature-controlled

cell are thought to be $\pm .0005$, while others are certainly better than $\pm .002$.

Garnets: The value N for the garnets were easily determined with precision using suitable oils on the temperature cell and equalizing the index with that of the mineral by raising or lowering the temperature.

Anthophyllite: The orientation in all anthophyllites is $Z=c$ and $Y=b$, and most cleavage fragments lie on a face elongated in this direction, facilitating precise determination of N_z . By turning the grains N_x could be measured, while N_y was measured on fragments displaying very low birefringence and an optic axis interference figure.

Amphiboles: Most amphiboles have a fairly distinct 010 parting and many grains in powders used for determination were found to lie on this plane. The indices N_x and N_z were measured on such grains displaying maximum birefringence, using a statistical method to ensure accuracy. By moving the coverglass it was possible to turn some of these grains over, and measure N_y , using interference figure and low birefringence as a guide.

Glinozoisite: Grains showing maximum birefringence were used to determine N_x and N_z on a statistical basis, while N_y was determined on grains with very low birefringence displaying an optic axis figure.

Anorthite: Inasmuch as powders of plagioclases are largely made up of 001 and 010 cleavage plates, and N_x' is nearly the same in either of these, the indices N_x and N_z could be determined by statistical examination of over 100 grains. Grains showing the least birefringence were used to determine N_y .

Optic Angle: Optic angle measurements were made on Emmon's 5 circle universal stage, on grains which had Bx_a nearly vertical so that direct measurement of the angle could be made by rotating the outer E-W axis from one optic axis to another. In view of the axial angle measurements being mostly over 75° , the estimated accuracy is only $\pm 1^\circ$, while those of smaller value may be as good as 0.5° , after index corrections. For each grain readings were taken at four positions and found to show little variability, though different grains particularly in the amphiboles showed variations of $\pm 3^\circ$. As pointed out by Hess (1949), optic angles obtained by plotting a bisectrix and one optic axis are rarely accurate due to several practical difficulties in obtaining a critical orientation of one of the optic vectors.

Dispersion: The dispersion of the optic axes were recorded by observing the intensity and distribution of color in the isogyres in acute bisectrix figures and also by observations on the universal stage during optic angle measurements. The dispersion of the optic angle has been determined by observing the values of the optic angle for violet and red light by use of filters.

Maximum extinction angle: The extinction angle ϕ Z for the amphiboles and pyroxenes were measured on the universal stage according to the method of Burri (1931), as the method recently developed and described by Hess (1949) could not be applied due to the paucity of twin crystals. It may be stated here that the accuracy of Burri's method is dependent on obtaining a critical orientation of the cleavage which involves a personal error of $\pm 2^\circ$, and hence the values for the extinction angle can

be estimated to have an accuracy of $\pm 2^\circ$. The values recorded in this paper are the averages of several determinations.

Pleochroism: Observations on the pleochroism of the amphiboles were made during optic angle and refractive index measurements.

Density: The density measurements on the minerals have been made at the Rock Analysis Laboratory, Minnesota, on the powders used for chemical analyses. The densities for the analyzed garnets have also been computed using the molecular weight and the edge of the unit cell as determined by x-rays.

Edge of Unit Cell: The a_0 constant for the garnets were described by x-ray diffraction analysis of finely ground powder using a Philip's x-ray spectrometer.

Modes: All the modes expressed in this paper are weight percentages, obtained by multiplying the volume percentages by the densities of the various minerals present. The modal measurements have been made by the point count method described by Chayes (1949). A clicker mechanism was installed on a Spencer mechanical stage* giving spacings of a third of a millimeter, and a Clay-Adams blood cell counter was used for tabulating the counts. This method of modal analysis is much less tedious than the usual methods and has none of the disadvantages of the various types of integrating stages. For the analyzed rocks, 10000 points have been counted to obtain a close approximation to the actual volumetric composition.

* I am indebted to Mr. Robert Witter for converting a mechanical stage for point-count analysis.

Twinning in Plagioclases: The determination of twin laws of plagioclase feldspars has been very popular, and several refinements have been made on the original methods of Berek, Reinhard and Duparc, particularly by Emmons (1943) and Turner (1947). The writer believes that a majority of these twin laws can be recognized by visual observation under the ordinary microscope, and in this connection a recent paper by Gorai (1950) is significant. Of the universal stage methods, the five-axis method of Emmons is perhaps the easiest and most practicable, as the older methods of Reinhard and the recent refinement of the same by Turner, using a four-axis stage, involve considerable amount of plotting transfers, etc., which to say the least are time consuming. In the present instance nearly 100 determinations have been made using the method of Emmons, and the writer's belief that many of the twinning laws can be deduced by visual inspection is based on this experience.

EXPLANATION OF TABULAR STATEMENTS OF CHEMICAL ANALYSES

The chemical analyses of the various minerals have been recast into their structural formula to determine their position in the mineral groups. For all calculations, the molecular values have been taken from the recent tables of Burri and Niggli (1945). The analysis of chromite has been recast after the method of Thayer (1946), in terms of molecular ratios of the RO and R_2O_3 constituents. For garnets the ratios of univalent, bivalent and trivalent metal atoms have been calculated from the analyses, as also the percentage of the various garnet 'Molecules'. The anorthite and albite contents for the complete and partial analyses of anorthite-

bytownite feldspars were calculated as the molecular ratios of CaO and Na₂O present. The analyses of amphiboles, clinozoisite and cordierite have been calculated and recast as follows.

Column 1 in the tabular statements give the weight percentages and column 2 the molecular ratios. Column 3 gives the oxygen ratios which are obtained by multiplying the molecular ratios of the various oxides by the number of oxygen atoms present. Column 4 gives the metal ratios which are derived by multiplying the molecular ratios by the number of metal atoms in each oxide. Next the number of oxygen atoms in the unit cell of the particular mineral are divided by the total oxygen atoms in column 3, to obtain a factor to calculate the equivalent metal atoms of each oxide. Column 5 gives the metal atoms obtained by multiplying the metal ratios by the factor mentioned above. Following Levin (1950), the ionic ratios are distributed to build the standard structure of the mineral.

One analysis of amphibole was recalculated from the rock analysis as it was the only ferromagnesian mineral present. The composition of the plagioclase was computed from optical and spectroscopic data, and the weight percentage of amphibole and plagioclase determined by point count analysis. By deducting the composition of the weight of plagioclase present from the rock analysis, the weights of the various oxides for the amount of amphibole present are obtained, from which the percentage composition was calculated.

The numbered specimens described in this paper are deposited in the Department of Geology, Princeton University, and are available for examination there.

PRINT IS VERY FAINT ON SOME OF
THE TABLES.

UNIVERSITY MICROFILMS

CHEMICAL COMPOSITION WITH MINERAL AND OPTICAL PROPERTIES OF SOME MINERALS FROM THE JITTANFUNDI COMPLEX, SALEM, INDIA

CONSTITUENT	1	2	3	4	5	6	7	8	9a	9b	10
SiO ₂	40.71	40.71	41.50	42.51	42.32	44.96	38.64	42.54	43.74	43.88	0.34
TiO ₂	0.55	0.08	0.08	0.13	0.27	0.23	0.14	0.03	-	0.00	0.36
Al ₂ O ₃	18.17	22.31	22.35	17.64	15.62	14.90	27.69	32.42	36.40	36.18	24.12
Fe ₂ O ₃	5.70	1.31	0.95	2.16	4.22	1.51	7.57	0.14	0.10	0.08	29.40
Cr ₂ O ₃	-	-	-	-	0.06	1.92	-	-	-	-	36.88
FeO	3.78	16.49	14.56	9.04	6.78	4.05	0.14	3.75	0.00	0.00	29.40
MnO	0.64	0.33	0.29	0.16	0.15	0.09	0.04	0.09	0.00	0.00	0.68
MgO	0.76	12.03	14.82	20.51	13.68	16.05	0.11	11.34	0.00	0.00	7.22
CaO	31.76	6.77	5.36	0.87	11.78	11.32	27.79	0.10	12.38	19.37	0.77
Na ₂ O	-	-	-	1.73	2.41	1.51	-	0.32	0.24	0.22	-
K ₂ O	-	-	-	0.00	0.34	0.12	-	0.01	0.04	0.00	-
H ₂ O ₊	-	-	-	-	-	-	-	-	-	-	-
H ₂ O ₋	0.13	0.23	0.36	0.12	2.13	2.26	1.34	1.32	0.37	0.28	-
H ₂ O ₊	0.06	0.09	0.09	0.09	0.11	0.15	0.10	0.02	0.04	0.08	-
CO ₂	-	-	-	-	-	-	-	-	-	-	-
Cl	-	-	-	0.05	0.03	0.05	0.07	0.00	-	-	-
F	-	-	-	0.02	0.02	0.02	-	0.01	-	-	-
Loss G for Cl+F	-	-	-	0.02	0.02	0.02	0.02	-	-	0.01	-
TOTAL	100.24	100.35	100.36	100.10	99.90	99.72	100.01	100.10	100.11	100.10	99.77
n _x	1.711±0.005	1.7615±0.005	1.7542±0.005	n _x =1.6415±0.005	1.6506±0.005	1.6402±0.005	1.7154-1.7102	1.5332±0.005	1.5754±0.004	-	-
D _{589nm}	3.685±0.005	3.835±0.005	3.786±0.005	n _y =1.6494±0.005	1.6611±0.005	1.6473±0.005	1.7158-1.7209	1.5433±0.005	1.5833±0.004	-	-

F_2O_5	-	-	-	-	-	-	-	-	-	-	-
H_2O^+	0.13	0.23	0.37	2.12	2.13	2.26	1.84	1.32	0.37	0.28	-
H_2O^-	0.06	0.09	0.09	0.03	0.11	0.15	0.00	0.03	0.04	0.08	-
CO ₂	-	-	-	-	-	-	-	-	-	-	-
Cl	-	-	-	0.05	0.03	0.05	0.07	0.00	-	-	-
F	-	-	-	0.02	0.02	0.02	-	0.01	-	-	-
Loss on heating	-	-	-	0.02	0.02	0.02	-	-	-	0.01	-
TOTAL	100.24	100.35	100.37	100.10	99.90	99.72	100.01	100.10	100.11	100.10	99.77
Wt. %	1.71 $\pm$ 0.005	1.7615 $\pm$ 0.005	1.7542 $\pm$ 0.005	$M_A=1.7415\pm0.005$	1.6506 $\pm$ 0.005	1.6402 $\pm$ 0.005	1.7174 $\pm$ 0.002	1.5302 $\pm$ 0.005	1.5754 $\pm$ 0.004	-	-
Density -	3.685 gm/cm ³ at 27.4°C	3.935 gm/cm ³ at 27.4°C	3.786 gm/cm ³ at 25.4°C	$M_F=1.694\pm0.005$	1.6611 $\pm$ 0.005	1.6473 $\pm$ 0.005	1.7158 $\pm$ 0.001	1.5483 $\pm$ 0.005	1.5733 $\pm$ 0.004	-	-
				$M_F=1.6772\pm0.005$	1.6638 $\pm$ 0.005	1.6565 $\pm$ 0.005	1.7076 $\pm$ 0.001	1.5462 $\pm$ 0.005	1.5607 $\pm$ 0.004	-	-
				$M_F=1.662\pm0.005$	-0.03 $\pm$ 0.00	-0.05 $\pm$ 0.00	-0.04 $\pm$ 0.00	-0.04 $\pm$ 0.00	-0.04 $\pm$ 0.00	-	-
				$M_A=1.64$	16 $\pm$ 1°C	10 $\pm$ 1	$M_A=1.64$	-	-	-	-
				3.167 gm/cm ³ at 26.4°C	3.167 gm/cm ³ at 26.4°C	3.117 gm/cm ³ at 26.4°C	3.130 gm/cm ³ at 26.4°C	2.591 gm/cm ³ at 27.4°C	2.753 gm/cm ³ at 26.5°C	2.749 gm/cm ³ at 26.5°C	-

0.12	1) Garnet, from enorthite gneiss, corundum quarries south of Sittampundi Salem district, Madras India. Analyst: Eileen K. Oslund.	0.70	6) Clinopyroxene, from enorthite hornblende gneiss from old quarry 1/4 mile west of K. Rangoli Hill, Salem District, Madras India. Analyst: Eileen K. Oslund.
0.41	2) Garnet, from rock 0.41. Analyst: Eileen K. Oslund.	0.71	7) Clinopyroxene, from enorthite hornblende gneiss from old quarry 1/4 mile west of K. Rangoli Hill, Salem District, Madras India. Analyst: Eileen K. Oslund.
0.60	3) Garnet, from enorthite hornblende gneiss (enorthite) east north east of Neduppaligam, Salem District, Madras India. Analyst: Eileen K. Oslund.	0.71	8) Clinopyroxene, from enorthite hornblende gneiss from old quarry 1/4 mile west of K. Rangoli Hill, Salem District, Madras India. Analyst: Eileen K. Oslund.
0.65	4) Anthophyllite, from enorthite anthophyllite hornblende rock, from quarry east north east of Pettiyarattar, Salem district, Madras India. Analyst: S. L. Goldich.	0.71	9) Clinopyroxene, from enorthite hornblende gneiss from old quarry 1/4 mile west of K. Rangoli Hill, Salem District, Madras India. Analyst: Eileen K. Oslund.
0.74	5) Clinopyroxene, from enorthite hornblende gneiss, collected west of Sittampundi, Salem District, Madras India. Analyst: Eileen K. Oslund.	0.71	10) Clinopyroxene, from enorthite hornblende gneiss from old quarry 1/4 mile west of K. Rangoli Hill, Salem District, Madras India. Analyst: Eileen K. Oslund.

Note: Analyses 1 to 6 made at Rock Analysis Laboratory, Minnesota, and 10 at the chemical and mineralogical Laboratory of W. K. Herdman. All hydrogen determinations by Mr. F. K. Murch of the Rock Analysis Laboratory. All density determinations by Rock Analysis Laboratory.

GARNET

Garnet is an essential constituent of the eclogitic rocks and of occasional occurrence in the anorthositic rocks. Chemical analyses of three garnets from these rocks show them to be of two dissimilar types, the eclogitic rocks carrying a pyropic garnet and the anorthositic rocks a grossularitic variety.

Garnet C.12 from anorthite-clinozoisite-corundum-garnet assemblage.

The chemical composition and physical properties of this garnet are shown in Table II. The composition of this garnet, $\text{GR}_{68}\text{AN}_{19}\text{AL}_9\text{PY}_{2.5}\text{SP}_{1.5}$, is unusual in having a fair amount of almandite and a little pyrope. The exhaustive list of analyses of garnets tabulated by Wright (1938) contains one analysis, $\text{GR}_{63.5}\text{AN}_{25}\text{AL}_{10}\text{PY}_0\text{SP}_{1.5}$, which is similar to the above, though it does not carry any pyrope. This garnet is stated to be from a serpentine contact, Heritsch (1927), and thus differs in paragenetic relations from our garnet. The following assemblages have been observed in the anorthositic series:

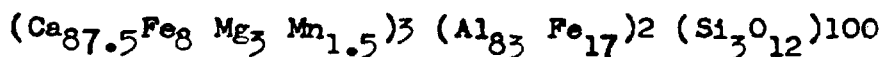
1. Anorthite, garnet, clinozoisite, corundum
2. Anorthite, garnet, clinozoisite, corundum, hornblende
3. Anorthite, garnet, vesuvianite(?)

In hand specimens the mineral has a pale brownish-red color and occurs as disseminated grains, together with clinozoisite and corundum, occasionally forming aggregates, simulating 'augen'. In thin section the mineral is mostly rounded, lacking any crystal form, and seen replacing anorthite resulting in a peculiar 'sieve' texture. It is difficult to distinguish this garnet from clinozoisite accompanying it, in plain light

COMPOSITION AND PHYSICAL PROPERTIES OF GARNET C.12

Weight percent		Ions	Metal ratio		Metal atoms	Ratio
SiO ₂	38.69	Si ⁴⁺	645		2.973	
TiO ₂	0.55	Ti	7	652	0.032	3.005
Al ₂ O ₃	18.17	Al ³⁺	356		1.641	
Fe ₂ O ₃	5.70	Fe	72	428	0.331	1.972
FeO	3.78	Fe ²⁺	53		0.244	
MnO	0.64	Mn	9		0.041	
MgO	0.76	Mg	19		0.091	
CaO	31.76	Ca	567	648	2.631	3.007
H ₂ O+	0.13					
H ₂ O-	0.06					
100.24		"Molecular" weight: 463.5				
		Analyst: Eileen K. Oslund				

Formula:



Garnet 'molecules' recalculated to 100 percent from above analysis

Grossularite	68.10
Andradite	18.70
Almandite	9.10
Pyrope	2.60
Spessartite	1.50
	<u>100.00</u>

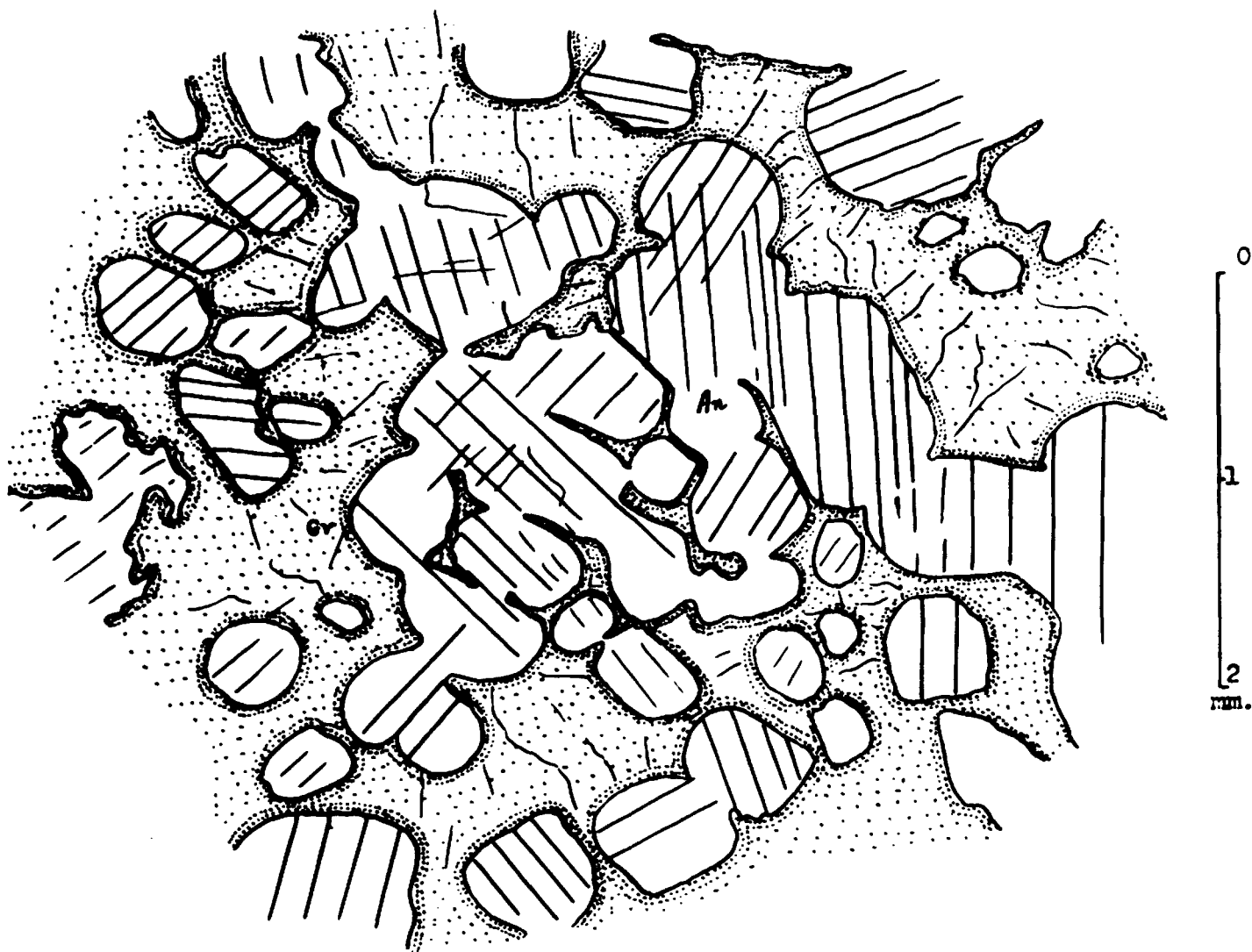
Determined density at 29/40°C	= 3.688 gm/cm ³
Calculated density based on values for end-members	= 3.687
Calculated density based on molecular weight from chemical analysis and on a ₀ as measured, using formula $G=1.65 \text{ WZ} / a_0^3$, where Z=8mols/cell	= 3.724
Measured value a ₀ for edge of unit cell	= 11.844 ± .005 Å
Calculated value of a ₀ based on values for end-members	= 11.855 Å
Refractive index N in sodium light	= 1.7692 ± .0005
Refractive index calculated from values of N for end-members	= 1.7739
Color:	brownish red in hand specimen; reddish brown at 80 mesh; pale brownish red in thin section.



Garnet replacing anorthite, in anorthosite X. 10



Garnet with dactylitic rims, in eclogite gabbro. X. 35

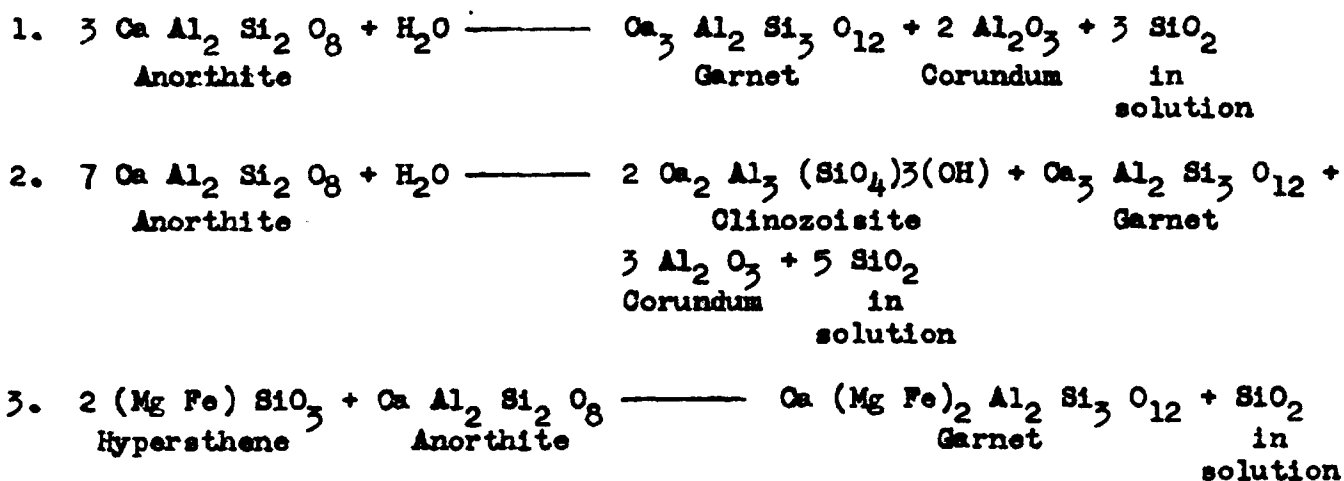


Garnet replacing anorthite in anorthite gneiss. Note 'atolls' of garnet around anorthite.

under the microscope, as a result of their similarity in color, refringence, and replacement relationship with anorthite.

In some thin sections, the garnets are seen to be enveloped by a mineral showing anomalous birefringence, and almost the same refringence and color as the garnet and clinozoisite. Duncan McConnell (1939) has drawn attention to the chemical and structural similarity of vesuvianite (idocrase) and grossularite, and the possibility of the presence of vesuvianite in the present assemblage cannot be ruled out, especially in view of the fact that H_2O must have played an important role in the evolution of these minerals. It may be mentioned here that the anomalous biaxial character of vesuvianite, as also its other optical similarities to clinozoisite, render the precise identification of the mineral difficult.

The following reactions are suggestive of the paragenesis of the garnet and related minerals:



The above reactions merely indicate the possible trends in the evolution of the garnet from an anorthositic rock, and other minerals such as

Table III

PHYSICAL PROPERTIES OF GARNET END MEMBERS

Name		A 2 ⁺ ion	B 3 ⁺ ion	N	G	n_o in λ	Mol. Weight
Pyrope	FY	Mg	Al	1.705	3.554	11.463	403.1
Almandite	AL	Fe	Al	1.830	4.325	11.518	497.6
Spessartite	SP	Mn	Al	1.800	4.196	11.613	494.9
Grossularite	GR	Ca	Al	1.735	3.582	11.863	450.4
Andradite	AN	Ca	Fe	1.895	3.838	12.068	508.1

REFRACTIVE INDICES OF SOME GARNETS WITH ESTIMATED COMPOSITION, AND THE COMPOSITIONS OF ASSOCIATED PLAGIOCLASE AND ORTHOPYROXENE

Rock type	N of garnet ± 0.0005	Composition of garnet	Ent% in ortho- pyroxene	Ant% of Plag.	Remarks
C.12 Anorthosite	1.7692	-	-	90%	garnet analyzed
C.40 "	1.7658	-	-	90%	-
C.19 Eclogite	1.7530	Mg ₅₅ Fe ₃₀ Ca ₁₅	84	-	-
C.36 "	1.7568	Mg ₅₁ Fe ₃₄ Ca ₁₅	86	55%	-
C.41 "	1.7615	Mg ₄₆ Fe ₃₅ Ca ₁₉	85.5	50%	rock and garnet analyzed
C.48 "	1.7568	Mg ₅₁ Fe ₃₄ Ca ₁₅	-	-	-
C.60 "	1.7542	Mg ₅₅ Fe ₃₁ Ca ₁₄	84	-	garnet analyzed
C.77 "	"	" " "	-	73%	-
C.122 "	1.7658	Mg ₄₅ Fe ₄₀ Ca ₁₅	85	55%	-
C.130 "	1.7580	Mg ₅₀ Fe ₃₅ Ca ₁₅	-	45%	-

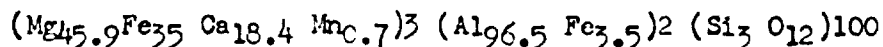
Note: Composition of garnets have been estimated from the values for N following Eskola (1921), except in the case of analyzed specimens.

Table IV

COMPOSITION AND PHYSICAL PROPERTIES OF GARNET C.41

Weight percent		Ions	Metal ratio		Metal atoms	Ratio
SiO ₂	40.71	Si ⁴⁺	678		3.003	
TiO ₂	0.08	Ti	1	679	0.004	3.007
Al ₂ O ₃	22.31	Al ³⁺	438		1.940	
Fe ₂ O ₃	1.31	Fe	16	454	0.070	2.010
FeO	16.49	Fe ²⁺	229		1.014	
MnO	00.33	Mn	5		0.022	
MgO	12.03	Mg	301		1.333	
CaO	6.77	Ca	121	656	0.536	2.905
H ₂ O+	0.23					
H ₂ O-	0.09					
100.35		"Molecular" weight: 464.3				
		Analyst: Eileen K. Oslund				

Formula:



Garnet 'molecules' recalculated to 100 percent from above analysis

Pyrope	41.40
Almandite	38.30
Grossularite	14.70
Andradite	4.20
Spessartite	0.90
	100.00

Determined density at 27/4°C	= 3.835 gm/cm ³
Calculated density based on values for end-members	= 3.874
Calculated density based on molecular weight from chemical analysis and on a ₀ as measured, using formula G=1.65 WZ /a ₀ ³ , where Z=8 mols/cell	= 3.971
Measured value a ₀ for edge of unit cell	= 11.556 ± .005 Å
Calculated value of a ₀ based on values for end-members	= 11.569
Refractive index N in sodium light	= 1.7615 ± .0005
Refractive index calculated from values of N for end members	= 1.7667

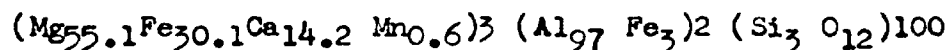
Color: pinkish red in hand specimen; pink at 80 mesh; and pale pink in thin section. Acicular inclusions seen occasionally.

Table V

COMPOSITION AND PHYSICAL PROPERTIES OF GARNET C.60

Weight percent		Ions	Metal ratio		Metal atoms	Ratio
SiO ₂	41.50	Si ⁴⁺	692		3.010	
TiO ₂	0.08	Ti	1	693	0.004	3.014
Al ₂ O ₃	22.35	Al ³⁺	438		1.905	
Fe ₂ O ₃	0.95	Fe	12	450	0.052	1.957
FeO	14.56	Fe ²⁺	202		0.878	
MnO	0.29	Mn	4		0.017	
MgO	14.82	Mg	371		1.613	
CaO	5.36	Ca	96	673	0.417	2.925
H ₂ O+	0.36					
H ₂ O-	0.09					
100.36		"Molecular" weight: 436.0				
		Analyst: Eileen K. Oslund				

Formula:



Garnet 'molecules' recalculated to 100 percent from above analysis

Pyrope	49.20
Almandite	33.00
Grossularite	14.20
Andradite	3.00
Spessartite	0.60
	<u>100.00</u>

Determined density at 25/4°C	= 3.786 gm/cm ³
Calculated density based on values for end-members	= 3.766
Calculated density based on molecular weight from chemical analysis and on a ₀ as measured, using formula $G = 1.65 W_z / a_0^3$, where Z=8 mols/cell	= 3.742
Measured value a ₀ for edge of unit cell	= 11.543 ± .005 Å
Calculated value of a ₀ based on values for end-members	= 11.557 Å
Refractive index N in sodium light	= 1.7542 ± .0005
Refractive index calculated from values of N for end-members	= 1.7561
Color: pinkish red in hand specimen; pink at 80 mesh; pale pink in thin section. Acicular inclusions seen occasionally.	

CHEMICAL COMPOSITION

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	H ₂ O+	H ₂ O-
1	41.52	Tr	23.01	1.22	0.22	12.86	0.33	16.64	4.71	0.16	
2	41.50	0.08	22.35	0.95	-	14.56	0.22	14.82	5.36	0.36	0.09
3	40.20	Tr	22.88	1.74	-	16.00	0.14	13.60	5.33	-	-
4	37.27	0.06	21.79	6.02	-	17.87	0.13	13.34	7.65	0.18	0.08
									Na ₂ O+K ₂ O=0.09		
5	39.39	Tr	24.75	2.55	-	12.65	Tr	12.54	7.71	-	-
6	39.64	0.26	24.19	1.15	-	13.63	0.33	12.90	7.98	0.08	
7	40.71	0.08	22.31	1.31	-	16.49	0.33	12.03	6.77	0.23	0.09
8	40.17	Tr	22.07	1.19	-	17.26	0.55	11.51	6.82	-	-
9	40.30	Tr	21.36	2.16	-	19.08	0.69	11.23	5.22	-	-
10	40.30	Tr	21.60	1.30	-	18.00	0.70	11.20	7.20	-	-

1. Garnet from eclogite, Rodvangen, Almklovdalen, Søndmore, Eskola (1921) p. 28, Anal.
2. Garnet from garnet pyroxenite, Anorthositkomplex i Heddal, Gjelevik (1947) p. 26.
3. Garnet from Kyanite eclogite, Silberbach, Fichtelgebirge, Dull (1953) p. 142, Anal.
4. Garnet from Hornblende plagioclase eclogite, Sittampundi complex, Salem, India, I.
5. Garnet from the eclogite from Silden, Nordfjord, Eskola (1921) p. 35, Analyt: I.

COMPOSITION AND PHYSICAL PROPERTIES OF ECLOGITE GARNETS

H ₂ O-	Total	RO	R ₂ O ₃	SiO ₂	Formula	N	G	Rock
0.16	100.67	2.92	1.00	2.95	(Fe ₂₆ Mn ₁ Mg ₆₁ Ca ₁₂) ₃ (Al ₉₇ Fe ₃) ₂	1.7498	3.782	Eclogite
0.09	100.36	3.014	0.379	2.925	(Fe _{30.1} Mn _{0.6} Mg _{55.1} Ca _{14.2}) ₃ (Al ₉₇ Fe ₃) ₂	1.7542	3.786	Eclogite gabbro
-	99.89	2.80	1.00	2.85	(Fe ₃₄ Mn _{0.3} Mg ₅₁ Ca _{14.7}) ₃ (Al _{95.5} Fe _{4.5}) ₂	1.755	3.730	Garnet-pyroxenite
0.08	100.32	2.58	1.00	2.51	(Fe _{27.6} Mn _{0.3} Mg ₅₁ Ca ₂₁) ₃ (Al ₈₅ Fe ₁₅) ₂	1.772	3.754	Eclogite
-	100.19	2.75	1.14	2.92	(Fe ₂₈ Mg ₅₀ Ca ₂₂) ₃ (Al ₉₆ Fe ₄) ₂	1.7610	3.758	Kyanite eclogite
0.08	100.16	2.93	1.08	2.97	(Fe _{28.7} Mn _{0.7} Mg _{48.9} Ca _{17.7}) ₃ (Al ₉₇ Fe ₃) ₂	1.756	3.760	Kyanite eclogite
0.09	100.35	3.00	1.05	2.90	(Fe ₃₅ Mn _{0.7} Mg _{45.9} Ca _{18.4}) ₃ (Al _{96.5} Fe _{3.5}) ₂	1.7615	3.835	Hornblende-plagioclase-eclogite
-	99.67	2.93	1.00	2.97	(Fe ₃₇ Mn ₁ Mg ₄₄ Ca ₁₂) ₃ (Al ₉₄ Fe ₆) ₂	1.7658	3.83	Eclogite in labradorite rock
-	100.59	2.83	1.00	2.93	(Fe ₄₀ Mn ₂ Mg ₄₃ Ca ₁₅) ₃ (Al ₉₄ Fe ₆) ₂	1.7660	3.882	Eclogite
-	100.30	3.02	0.985	3.01	(Fe _{37.4} Mn _{1.5} Mg _{41.8} Ca _{19.3}) ₃ (Al _{96.4} Fe _{3.6}) ₂	1.756	3.74	Eclogite

p. 28, Analyst: P. Eskola. 2. Garnet from garnet pyroxene rock (eclogite gabbro), Sittampundi complex, Salem, India. Analyst: Eileen K. Oslund

1947) p. 25, Analyst: Gjelsvik. 4. Garnet from eclogite, Greenland Sahlstein (1935) p. 16, Analyst: Th. G. Sahlstein

p. 148, Analyst: W. Dull. 6. Garnet from eclogite, Weissenstein, Bavaria, Tilley (1936) p. 425, Analyst: Hilda Bennet

, India, Analyst: Eileen K. Oslund. 8. Garnet from eclogite inclusion in labradorite rock from Indre Sogn, Eskola (1921) p. 34, Analyst: P. Eskola

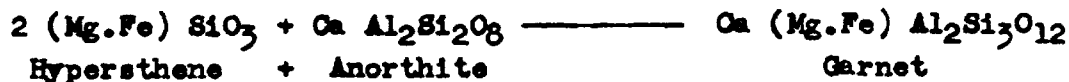
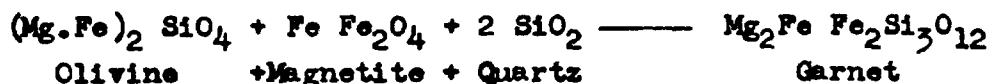
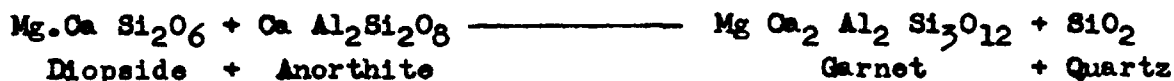
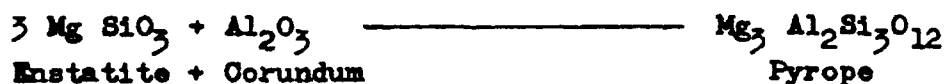
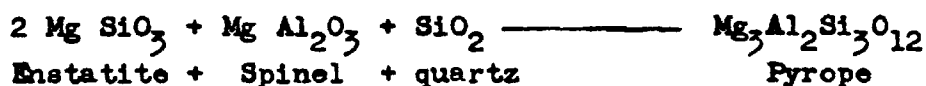
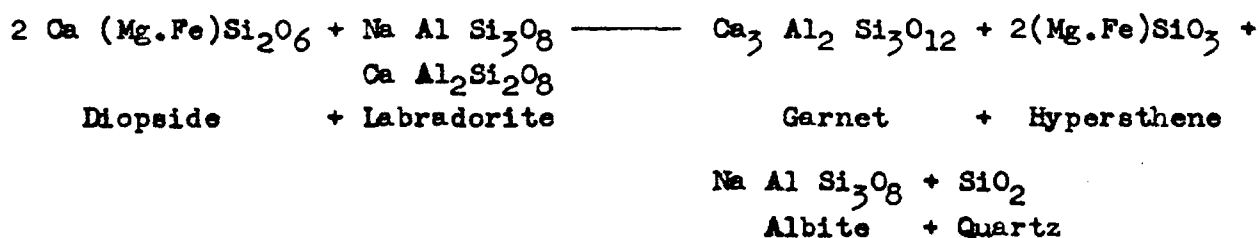
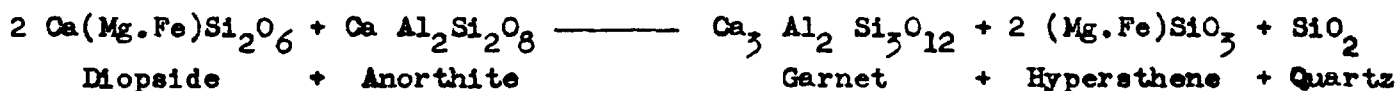
Analyst: P. Eskola. 10. Garnet from eclogite, half mile east of north of Bienn a' Chapuill, Alderman (1936), p. 498, Analyst: W. Pollard

augite must have partaken in these reactions to produce a grossularitic garnet with a fair proportion of andradite and small amounts of almandite and pyrope. The close association of corundum, clinozoisite and garnet in anorthitic rocks lends support to the above suggestion. The several massive quartz veins within the anorthositic belt may perhaps represent the SiO_2 released during the formation of the above minerals.

Garnets C.41 from Hornblende garnet plagioclase rock (Eclogite gabbro), and C.60 from Pyroxene garnet rock (Bronzitic pyropite). The garnets from these rocks are chemically similar to each other and different from those found in the anorthositic rocks. These garnets are pyralmandites with a small proportion of grossularite, andradite and spessartite. The chemical composition and physical properties of these two garnets are tabulated in Tables IV and V, and Table VI shows the chemical composition and physical properties of eclogite garnets. The two garnets analyzed appear to be typical eclogite garnets. These garnets are essential constituents of the eclogitic rocks, making up from 25 to 50%, and in an exceptional type up to 80%, by weight of the rock. In thin section they are seen to be distributed as rounded crystals varying from one to four millimeters in diameter in a matrix of kelyphite or pyroxenes. The rocks display remarkable corona structures and plagioclase-diopside-hornblende symplectites.

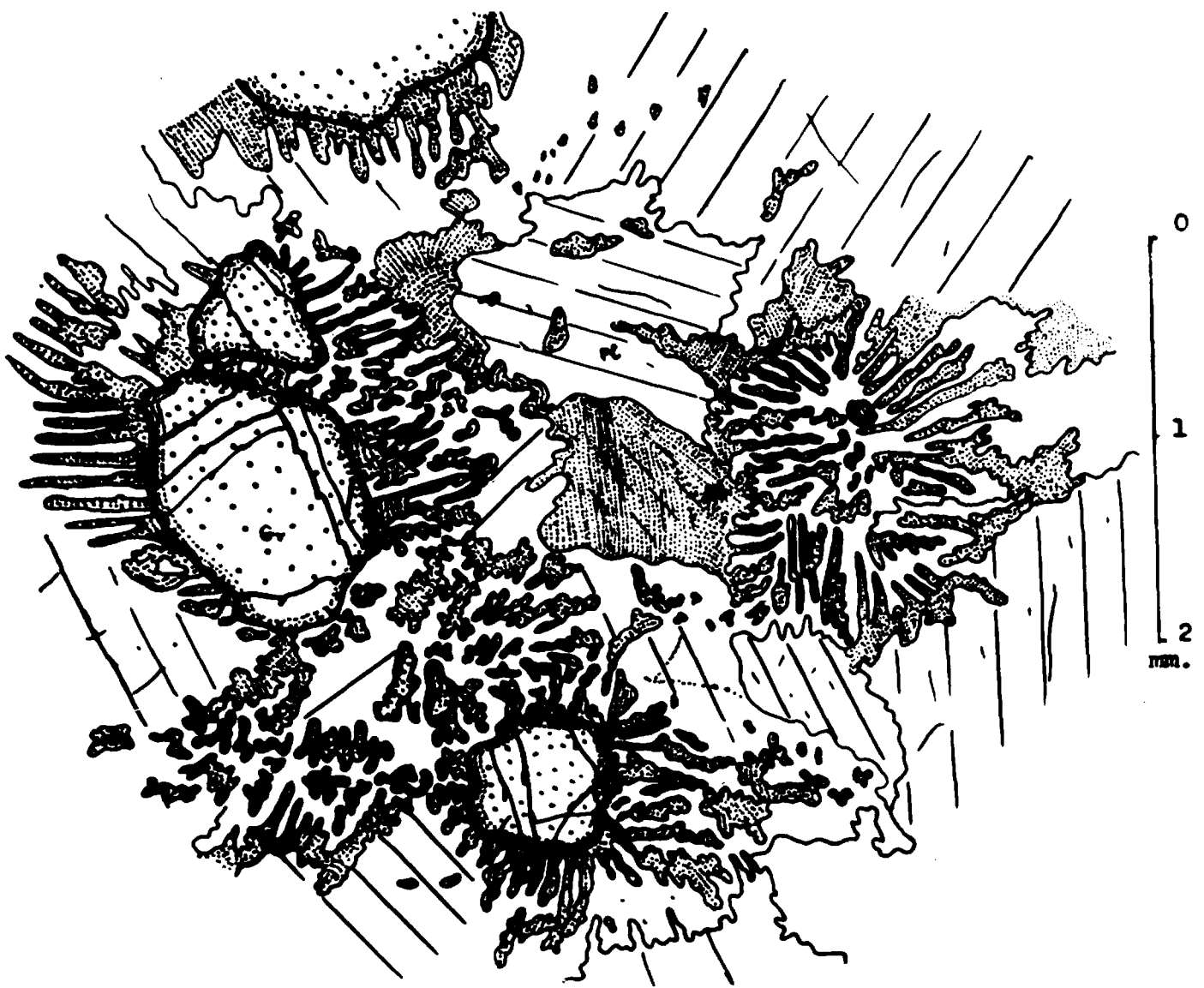
The paragenesis of garnets in gabbroidal and eclogitic rocks has been discussed by several petrologists and among others Ghosh (1941) and Davidson (1943) have suggested several equations indicating prograde reactions. It may be stated that these reactions oversimplify the problem

of the evolution of garnets, but help in a proper appreciation of the various chemical reactions operative in their formation. Some of these reactions are outlined below.



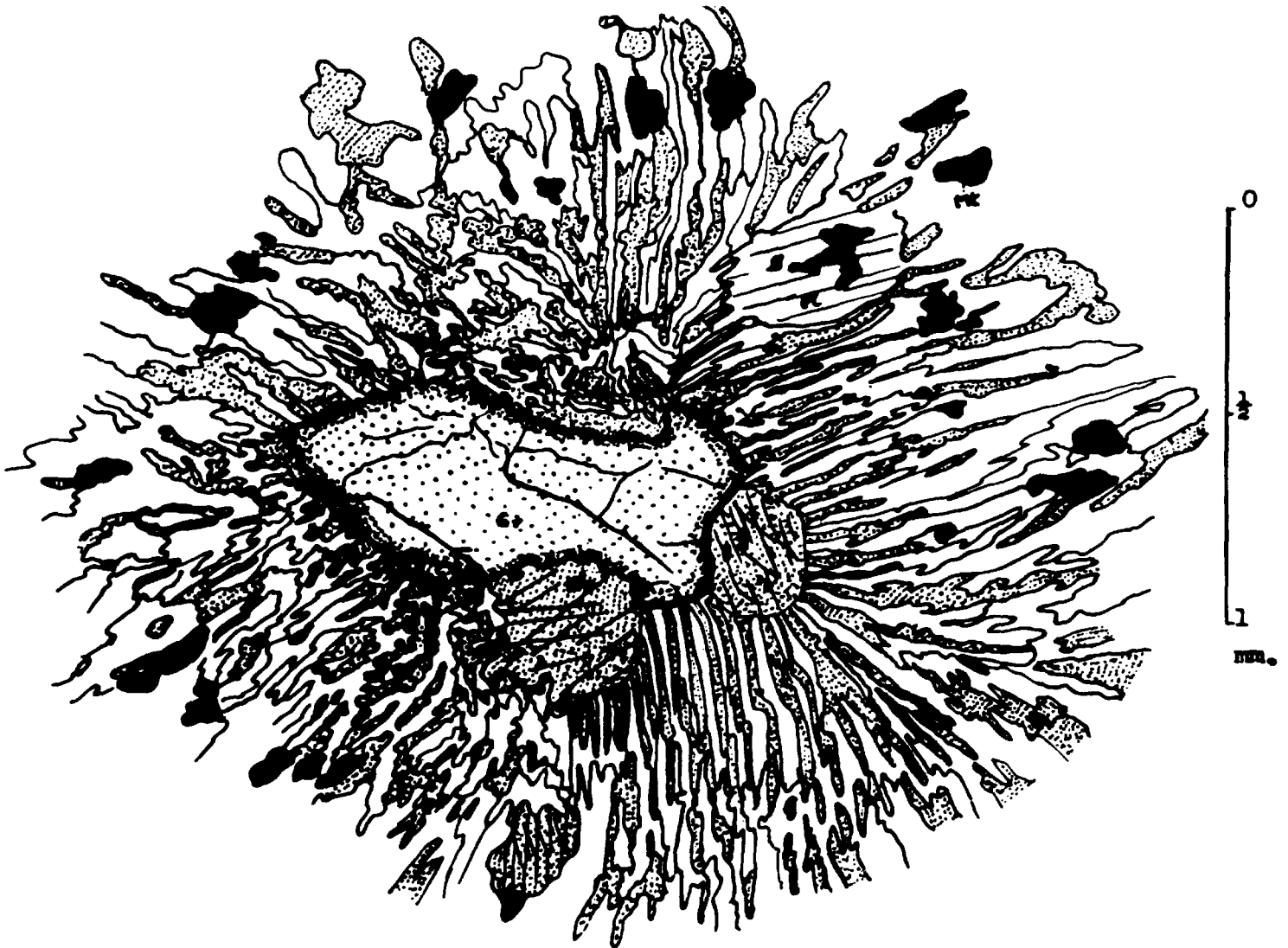
The paragenetic relationships of the ferromagnesian minerals, plagioclase and garnet in the eclogitic rocks is suggestive of some of the above reactions.

PLATE XIII



Garnet in eclogite gabbro. Note symplectite of hornblende
and plagioclase around garnet
forming a 'corona'

PLATE XIV



Garnet in eclogite gabbro. Note corona of hornblende
and plagioclase symplectite. Drawing
from thin section shown in Plate. 35

Eskola (1921), Heritsch (1927) and Wright (1938) have suggested compositional ranges for eclogite garnets, and these are tabulated below, together with the compositional range deduced by the writer for true eclogite garnets from the literature.

Composition of Eclogite Garnet

<u>End member</u>	<u>Heritsch</u>	<u>Eskola</u>	<u>Wright</u>	<u>APS</u>
Grossularite	9-42%	9-20%	5-41%	12-22
Andradite	0-21	2-11	4-20	3-15
Almandite	33-57	26-61	6-66	25-40
Pyrope	19-37	16-61	10-81	42-61
Spessartite	0-3	1-2	1-12	0-2

Further discussion of the eclogite problem and the importance of the chemical composition of the garnet will follow in a later section.

PLAGIOCLASE FELDSPARS

The most abundant silicate mineral in the rocks of this complex is plagioclase feldspar, which ranges in composition from An₇₅₋₁₀₀ in the anorthosites to An₄₅₋₇₀ in the eclogite gabbros. The feldspar in the anorthosite was described by Count de Bournon in 1802 and identified by him as a new mineral Indianite in 1817. Three more chemical analyses of this feldspar were published before Lacroix (1889) presented the optical properties of this anorthite supported by a new chemical analysis. Petrographic examination of these rocks by the writer indicated that the composition of the calcic feldspar was very variable, thereby showing that the older analyses did not necessarily represent the most calcic feldspars. A very pure sample of this feldspar was separated from rock

C.50, and chemically analyzed. As a check on this analysis, the same sample was refined further and analyzed again. These analyses together with the older analyses are presented in Table VII.

Mr. Joensuu, Spectroscopist at the Geology Laboratory of the Chicago University,* kindly made spectroscopic determinations on 12 different specimens of calcic feldspar from these rocks. He devised a new technique for these analyses using the continuous arc method, with Li as an interval standard for Na and Sr as an interval standard for Ca. As absolute standards for comparison, glasses of the composition of pure anorthite, and $Ab_1 An_5$ were used by him as well as an analyzed albite supplied by the Bureau of Standards. These determinations are stated to have an accuracy of $\pm 10\%$, and the results are presented in Table VII.

A review of the literature showed that up to date only 87 analyses of anorthite have been published, 20 of them before 1850, 46 between 1850 and 1900, and 21 since then. Most of these analyses do not conform to present day standards of accuracy, and in many of them several constituents have not been determined. In Table VIII five analyses of anorthites from the literature and their physical properties, together with three new analyses of anorthites, are presented. Two of these are of Sample C.50, while the third is a new analysis of anorthite occurring in allivallite ejected from Hakone volcano, Japan, reproduced here through the courtesy of Dr. Hisashi Kuno. As may be seen from the tabular statement, most of the known anorthites are from high temperature rocks, and

* I am indebted to Dr. J. R. Goldsmith for arranging to have these determinations carried out.

Table VII

CHEMICAL COMPOSITION OF ANORTHITE FROM SITTAMPUNDI

	1	2	3	4	5	6	7
SiO ₂	42.50	42.00	43.00	42.09	42.80	43.74	43.88
Al ₂ O ₃	37.50	34.00	34.50)	38.89	38.06	36.40	36.18
Fe ₂ O ₃	3.00	3.20	1.00)		-	0.10	0.08
CaO	15.00	15.00	15.60	15.78	19.31	19.38	SrO 19.37+0.01
Na ₂ O	-	3.35	2.60)	4.08	Tr	0.24	0.22
K ₂ O	-	-	-)			0.04	0.00
H ₂ O+)	2.00	1.00	1.00	-	-	0.37	0.28
H ₂ O-)						0.04	0.08
Total	100.00	98.55	97.70	100.84	100.17	100.30	100.10
Arg%	89	83	87	81	96	97.5	98

1 quoted from Chenevix (1802) p.334. 2 & 3 quoted from Lacroix (1889)
 4 quoted from Silliman (1849) p.391. 5 quoted from Lacroix (1889)
 6 & 7 new analyses of C.50. FeO, TiO₂, MgO and MnO totally absent.

PARTIAL SPECTROSCOPIC ANALYSES OF SOME ANORTHITIC FELDSPARS

<u>Sample No.</u>	<u>Na₂O</u>	<u>CaO</u>	<u>An</u>	<u>Ab</u>
C.6	1.72	17.6	85.3	14.7
C.14	1.20	18.3	90.0	10.0
C.28	0.50	20.0	95.7	4.3
C.33	1.17	18.8	89.8	10.2
C.40	1.12	19.0	90.3	9.7
C.50	0.17	19.7	98.6	1.4
C.52	1.40	18.1	87.5	12.5
C.69	0.95	18.0	91.3	8.7
C.82	1.60	18.1	86.1	13.9
C.86	2.45	15.0	77.2	22.8
C.96	0.10	20.0	99.1	0.9
C.128	1.80	17.7	84.4	15.6

Analyst: Mr. Oiva Joensuu, Department of Geology, University of Chicago.

CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF SOME ANORTHITES

Number:	1	2*	3*	4*	5*	6*	7	8
Author:	P.S.Miller	S.Kozu	J. Kratzert	Z.Harada	S.Tsuboi	H.Kuno	A.P.Subramaniam	
Locality:	California	Japan	Vesuvius	Japan	Japan	Japan	India	
SiO ₂	43.77	44.49	43.34	43.91	43.54	44.24	43.74	43.888
TiO ₂	-	-	-	-	Tr	-	-	0.00
Al ₂ O ₃	36.11	36.00	35.31	35.98	35.66	35.75	36.40	36.18
Fe ₂ O ₃	0.09	0.08	0.65	0.15	0.58	0.64	0.10	0.08
FeO	-	-	-	0.18	0.00	-	0.00	-
MnO	-	-	-	-	Tr	-	0.00	-
MgO	0.07	0.04	0.17	0.14	0.06	-	0.00	0.00
CaO	18.73	19.29	19.93	19.58	19.53	18.88	19.38	19.37
Na ₂ O	0.67	0.59	0.39	0.48	0.26	0.16	0.24	0.22
K ₂ O	0.11	0.03	0.36	0.03	Tr	0.04	0.04	0.00
P ₂ O ₅	-	-	-	-	Tr	-	-	SrO 0.01
H ₂ O+	0.40	-	0.21	0.20	0.20	-	0.37	0.28
H ₂ O-	-	-	-	0.18	0.10	-	0.04	0.08
Total	99.95	100.72	100.36	100.83	99.93	99.71	100.31	100.10
Analyst:	F.A.Gonyer	H.S.Washington	J.Kratzert	T.Nemoto	S.Tanaka	Ind.Chem. Lab.Tokyo	S.S.Goldich & E.K.Oslund	
Density	2.759	-	2.760	-			2.753	2.749
Anorthite%	93.3	94.6	95.0	95.6	97.6	98.3	97.5	98.0
Albite%	6.0	5.1	3.3	4.2	2.4	1.5	2.2	2.0
Orthoclase%	0.7	0.3	1.7	0.2	?	0.2	0.3	0.0
N _X	1.574	1.5747	1.5751	-	1.576	1.5752±.0004**	1.5754±.0004	
N _Y	1.582	1.5827	1.5830	-	1.584	1.5828±.0004	1.5833±.0004	
N _Z	1.586	1.5880	1.5882	-	1.588	1.5882±.0004	1.5885±.0004	
2V	-79°	-77° 16'	-77° 10'	-	-78°	-79°	76.3 to 77.7	
Dispersion	weak r < v	-	-	-	(very weak r < v)	-	r < v weak	
Year Published	1935	1914	1921	1933	1935	-	-	

* High temperature anorthites from effusive rocks.

** Determined by A.F.S.

the most calcic feldspar recorded in a plutonic rock is $An_{93.3}$ in a hornblende olivine anorthite gabbro, described by Miller (1935).

Sample C.50 and An_{98} is without doubt from a rock formed at a much lower temperature, which has subsequently undergone chemical transformations and recrystallization.

Dr. Bowen, who is at present investigating high and low temperature plagioclases by means of x-rays, kindly examined some of these anorthites and indicated a value of An_{99-100} for sample C.50. Dr. Goldsmith determined the minimum melting temperature of sample C.50 to be $1548^{\circ}C$, only 5° less than the accepted melting point of pure synthetic anorthite.

OPTICAL PROPERTIES

Lacroix (1889) has made an excellent optical study of this feldspar and established its identity with anorthite. His description translated by Mallet (1891) follows:

The anorthite constitutes nine tenths of the rock, which occurs in granular masses, the individual grains in which measure about half a millimetre in their longest direction. Usually white, it sometimes becomes pink or greenish owing to the presence of fine crystals of garnet, hornblende etc.

The feldspar is fusible before the blow-pipe to a white glass and is easily attacked by hydrochloric acid, although preserving its form; it possesses all the properties of typical anorthite.

Microscopic sections show the anorthite in the form of rounded grains, the contact lines between which are often rectilinear. Twinning occurs on the charlsbad, albite and pericline types, but untwinned crystals are not uncommon. The form of the hemitrope plates on the albite type is most varied: sometimes a patch is composed of two or three large bands; sometimes on the other hand, there is a very large number of more or less narrow ones, but always very regular and not presenting any trace of dynamic phenomena.

Very often carlsbad twinning is superposed on that of albite.

The hemitrope-lamellae on the pericline type are only observed as a rule, in the midst of some of the bands belonging to the albite twinning.

Extinctions in parallel light take place in the zone perpendicular (010) at very large angles - as much as 45° .

Extinction on a plate parallel to the principal cleavage (001) occurs at 39° from the edge of (001) and (010) faces. Owing to the small thickness of such plates, I have not been able to obtain any parallel to the second cleavage (010).

During the examination of a great number of sections, I succeeded in finding some sufficiently nearly perpendicular to the three principal axes of the ellipsoid of the indices, and in measuring their difference by means of Michel Levy's comparateur we have-

$$N_Z - N_X = 0.013$$

$$N_Z - N_Y = 0.007$$

$$N_Y - N_X = 0.008$$

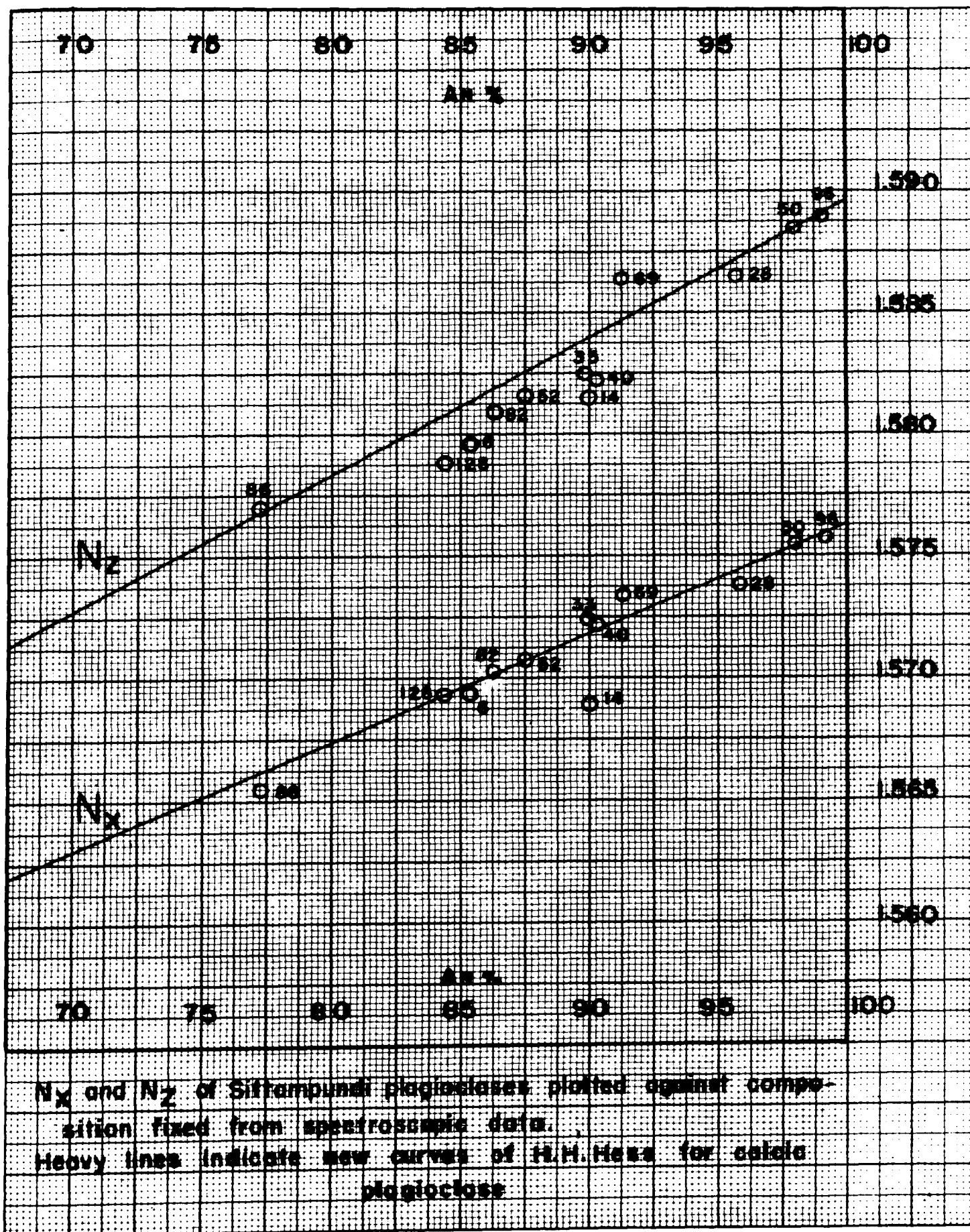
The bisectrix is negative X. In the section perpendicular to the bisectrix, the trace of the plane of the optic axis makes an angle of 41° with the trace of the twinning of the albite type.

$$2 E = \text{about } 130^{\circ}$$

The principal indices of refraction N_X and N_Z were measured on cleavage fragments by the immersion method, using a temperature cell and closely spaced calibrated oils. For the analyzed specimen the values N_X , N_Y and N_Z were measured several times to ensure accuracy. The value N_Y was determined on the Universal stage with great precision by the following method. A grain of the feldspar showing low birefringence was removed from a thin section and mounted on the Universal stage, using a liquid with a slightly higher index of refraction than N_Y of the feldspar,

as mounting medium. After allowing the setting to attain room temperature, the plate of plagioclase was oriented with N_X vertical, and N_Z and N_Y in a plane parallel to the microscope stage. The N_Y of the plagioclase was observed to be lower than that of the liquid for the above orientation. The microscope stage was then rotated until the index of the liquid was the same as that of the crystal for a particular direction, and the angle of rotation recorded. It is well known that crystal rotated on the Universal stage may cause changes in transmitted light in vibration direction and therefore in refractive index. Within the planes of optic symmetry of a crystal, the change in refractive index with changes of vibration direction are according to the equation of the ellipse. Having previously determined the birefringence and optic axial angle of the plagioclase, the partial birefringence $N_Z - N_Y$ could be calculated. With this figure, and the number of degrees of rotation on the microscope stage from N_Y towards N_Z , the amount to be subtracted from the index of the liquid to obtain N_Y (or added to obtain N_Z), could be determined using Emmons' chart (plate 10, G.S.A. Memoir 8), which is a graphical solution of the equation of the ellipse. This method may be adopted for measurement of indices of certain minerals under the ordinary microscope, if they have a cleavage or parting parallel to one of the principle optic indicatrix planes.

The birefringence of this anorthite was determined by Professor Hess, following his own technique (1949). The optic axial angle was measured on several grains which showed emergence of both the optic axes and the dispersion of optic angle recorded by use of filters. The



physical and optical properties of anorthite C.50, together with some of the properties of synthetic anorthite are shown below.

<u>Optical and physical properties of anorthite C.50</u>		<u>Optical properties of synthetic anorthite*</u>
N_X	= 1.5754 ± .0004	1.5760 ± .0004
N_Y	= 1.5833 ± .0004	1.5838 ± .0004
N_Z	= 1.5885 ± .0004	1.5895 ± .0004
Birefringence $N_Z - N_X$	= 0.0131	0.0135 - 0.0133****
$2 V_X$	= 76.8, 76.9, 77.6, 77.7 Average value = 77.2°	-80° - 75.2° **** (Calculated)
Dispersion	= r < v weak	-
Cleavages:	001 and 010 well developed	-
Twinning:	Albite, Baveno, Manebach, Acline, Carlsbad, Pericline, Albite-Ala, Carlsbad-albite, and Manebach Ala.	-
Density	= 2.749 to 2.753 gm/cm ³ at 26.5/4°C	2.765 gm/cm ³ **
Minimum melting temperature	= 1548°C	1553°C ***
Color:	Snow white, transparent crystals	White
Alteration:	Incipient, occasionally to calcite and scapolite, easily attacked by strong HCl.	-
Note:	Extinction and cleavage angles were measured on the Universal stage, but it will require several hundreds of determinations to arrive at precise values.	-

The principal indices of refraction, optic axial angles and anorthite contents of some of these calcic feldspars are presented in Table IX. The An contents have been read off from a curve recently drawn by

* Measured by writer on specimen from Geophysical Laboratory.

** Value determined by Geophysical Laboratory.

*** Melting point of pure anorthite (synthetic).

**** Measured by H. H. Hess.

Table IX

ANORTHITE CONTENT OF FLAGIOCLASES IN SITTAMPUNDI ROCKS
BY VARIOUS METHODS

No.	2V $\pm$ 1°	An% ₁	N _X $\pm$.0008	An% ₂	N _Z $\pm$.0008	An% ₃	An% by 'U' stage	An% from spectroscopic data
C.4	-79,-80,-81	85,88,90	1.5726	89.0	1.5826	87.5	-	-
C.6	-81,-82	84,85	1.5694	84.5	1.5796	82.0	-	85.3
C.11	-	-	1.5634	71.5	1.5715	68.0	-	-
C.14	-80,-81,-82	84,85,88	1.5688	84.0	1.5812	85.0	-	90.0
C.27	-	-	1.5686	84.0	1.5733	80.0	-	-
C.28	-77.5,-78,-79	91,94,96	1.5738	94.5	1.5864	94.5	-	95.7
C.33	-78,-79,-80	87,91,94	1.5724	89.0	1.5824	87.5	90,92,95, 98,99	89.8
C.34	-78,-79,-80	87,91,94	1.5686	87.0	1.5816	85.5	-	-
C.35	-	-	1.5640	70.0	1.5736	71.5	-	-
C.39	-78,-79,-80	87,91,94	1.5718	88.0	1.5824	87.5	-	-
C.40	-	-	1.5724	91.0	1.5822	87.5	-	90.3
C.41	+77,+78,+79	55,56,58	1.5531	48.0	1.5608	48.0	54,56,58	-
C.50	-77,-77.5,-78,-79	91,94,96,100	1.5754	98.0	1.5885	98.0	92,94,96, 98,99,100	98.0
C.52	-80,-81	85,87	1.5708	87.0	1.5816	85.5	-	87.5
C.53	-	-	1.5696	85.0	1.5816	85.5	-	-
C.54	-	-	1.5662	77.0	1.5772	73.0	-	-
C.58	-80	85	1.5686	84.0	1.5806	84.0	-	-
C.66	-	-	1.5686	84.0	1.5806	84.0	-	-
C.69	-78, 79,-80	87,91,94	1.5735	92.5	1.5864	94.5	90,92,94	91.3
C.71	-79,-81,+84	67,84,94	1.5642 1.5718	72.5 90.0	1.5737 1.5838	72.0 90.0	60,66,70 88,92,95	-
C.77	-	-	1.5636	71.5	1.5742	72.5	-	-
C.82	-80,-81,-82	84,85,87	1.5705	87.0	1.5808	84.5	-	86.1
C.86	-86	77	1.5655	76.0	1.5770	77.5	-	77.2
C.88	-	-	1.5672	80.0	1.5754	75.0	-	-
C.96	-76,-76.5,-77	100	1.5758	100.0	1.5888	99.0	100	99.1
C.117	-	-	1.5681	81.5	1.5731	79.5	-	-
C.119	-	-	1.5706	87.0	1.5807	84.0	-	-
C.120	-	-	1.5706	87.0	1.5812	85.0	-	-
C.122	+78,+80	55,60	1.5527	48.0	1.5607	48.0	58,61	-
C.128	-83	82	1.5692	84.0	1.5788	81.0	-	84.4

Note 1) An% deduced from optical data using a new set of curves by Professor Hess.

2) An% on 'U' stage by Ermons, Five-Axis-Method.

3) Spectroscopic data by Mr. Joensuu of Chicago.

4) An% for sample C.50 from chemical analysis

Professor Hess, correlating the An content, refractive indices and $2V$ of Plagioclases for compositional range An_{65} to An_{100} . The anorthite contents of twelve specimens calculated from spectroscopic data are also included in the tabular statement. In Plate 5 these values have been plotted, together with Professor Hess's curves for N_X and N_Z . It may be seen that most of the determined values for N_X fall very close to the N_X curve while values of N_Z tend to lie below the curve between An_{80} and An_{90} . This is in conformity with Tsuboi's (1923) view that N_X would be almost the same irrespective of the orientation of the cleavage.

TWINNING

Twinning laws in plagioclase feldspars have received recent attention from mineralogists and the most significant contributions on the subject are those of Gorai (1950) and Turner (1951), who arrived at almost identical conclusions independently. Gorai, after a statistical analyses of thousands of plagioclase twins in common igneous and metamorphic rocks, has classified the twins into two types 'A' and 'C'. The 'A' type includes the Albite, Pericline and Acline twins and the 'C' type the Carlsbad, Carlsbad-albite, Baveno, Ala, Manebach, Manebach Ala, and Albite-Ala twins. Gorai considers the 'C' type to be characteristic of plagioclases in rocks crystalized from a melt, and the 'A' type characteristic of metamorphic and metasomatic rocks. Turner has analyzed the question of twinning of plagioclase in rocks on the basis of his own observations and those in the literature, and reached similar conclusions. Turner points out that in amphibolites of igneous origin, coarse plagioclase is liable to show twinning just as complex as that of igneous



CRYSTAL OF ANORTHITE EXHIBITING COMPLEX-ALBITE ALA TWINNING
IN ANORTHITE CLINOZOISITE ROCK. NOTE CLINOZOISITE
REPLACING ANORTHITE.

plagioclase. The twinned condition and crystal habit of such plagioclases are considered by him to be relict and indicative of the igneous parentage of the amphibolite, in which they are observed.

The plagioclases in the Sittampundi rocks consist of an equal proportion of twinned and untwinned individuals. In Table X the results of twin determinations, following Emmons (1943), carried out on the plagioclases of these rocks are presented. Following Gorai, there are 54 'A' twins and 36 'C' twins in a total of ninety determinations. While in general these plagioclases exhibit twinning tendencies indicative of metamorphic rocks, the presence of fair proportion of 'C' type twins definitely points to an igneous parentage for these enigmatic rocks. It is believed that much of the twinning of the plagioclases in these rocks was obliterated during deformation and recrystallization of the complex. This is indicated by the polysynthetic twins of labradorite in the eclogite gabbros displaying bent twin lamellae, and in some cases their disappearance from portions of a crystal. This again is in conformity with Turner's conclusion that plagioclases in tectonites, resulting from deformation proceeding simultaneously with crystallization, lamellar twinning is on the whole much less developed. Emmons and Gates (1943) consider twinning in plagioclases a secondary phenomenon, while Donnay considers it to be a function of crystal growth controlled by the geometry of the space lattice. Observations on the twinning in Sittampundi rocks lends support to Donnay's view. If twinning is an external phenomenon and essentially secondary as contended by Emmons, one would expect to find an abundance of twins in slightly deformed recrystallized rocks, in

Table X

TWINNING LAWS OF PLAGIOCLASE FELDSPARS IN THE SITTAMPUNDI ROCKS

Normal Twins							
Type of twin	C.33	C.41	C.50	C.69	C.71	C.122	C.128
Albite	4	3	6	2	2	1	3
Baveno	1	+	1	+	1	+	+
Manebach	3	+	2	2	2	+	1
Parallel Twins							
Accline	4	+	2	1	1	+	1
Ala	+	1	+	+	+	2	+
Carlsbad	1	2	1	+	+	2	+
Pericline	6	1	6	3	3	1	4
Complex Twins							
Albite-Ala	2	+	2	2	1	+	+
Carlsbad-albite	1	1	1	1	+	1	+
Manebach-Ala	+	+	1	+	+	+	+
Manebach-Accline	+	+	+	1	+	+	+
Total	22	8	22	12	10	7	9

'A' twins (albite, accline, pericline) 54

'C' twins (Manebach, Ala, Baveno, Carlsbad)
(albite-Ala, Carlsbad-albite,) 36
(Manebach-Ala, Manebach-Accline)

C.33, C.50, C.69, C.128, Rocks of the anorthosite series.

C.41, C.122, Rocks of the eclogite gabbro series.

C.71 Cordierite-corundum-anthophyllite rock.

which mutual interference of grains and other factors considered to favor twinning, are the order.

In general a compositional variation of 2% An is indicated in most of the rocks and occasionally as much as 3%. This was apparent during index determinations when a statistical basis had to be adopted to avoid inconsistencies. The co-existence of feldspars of two compositions in the same rock is in accordance with Buerger's concept that natural feldspars found before their ordering temperature will not be in the form of solid solution crystals. It is believed that chemical transformations during metamorphism have contributed to the formation of feldspars of varying composition in the same rock.

The plagioclase feldspars in the eclogite gabbros range in composition from An_{48} to An_{72} , and bear evidence of their igneous parentage by displaying a fair proportion of 'O' twins. Some of the larger crystals contain bands of regularly arranged inclusions, which have lower index of refraction than the host of feldspar, indicating them to be liquid or gas inclusions. Professor Hess* has noticed similar inclusions in the ground mass feldspar of some stony meteorites. The presence of such inclusions in these eclogites must therefore be considered to indicate their original igneous character.

The plagioclases in the anorthosite series are very calcic and fall within the compositional range An_{75} to An_{100} . They are generally 1 to 2 mm in length, but occasionally crystals up to 5 cms in length are encountered in some of the pegmatitic rocks. In thin sections of rocks

* Oral communication.

they have subhedral boundaries, imparting a mosaic texture. They are exceptionally fresh and devoid of inclusions and secondary alteration products, though scapolitization is noticed occasionally. They are also seen to be replaced by clinozoisite, garnet and corundum. The following conclusions have been reached on the basis of the above study.

1. The anorthositic rocks of this complex contain calcic plagioclase exceptionally rich in the anorthite molecule, as indicated by the chemical analysis of one sample, spectroscopic analyses of twelve samples, and optical study of nearly forty samples from different rocks. Samples C.96 and C.50, with anorthite contents of 99.1% and 98%, indicated by spectroscopic and chemical analyses respectively, represent the purest specimens of natural anorthite known so far.

2. Several optical methods were tried to obtain the composition of these feldspars and it was found that the indices of refraction were susceptible to perceptible changes for small variation in composition. It was also found that values of N_x measured on grains were better suited for fixing the composition as it was nearly the same for cleavage fragments on both (001) and (010).

3. A statistical analysis of the twinning laws of plagioclases in these rocks indicate an igneous parentage. The fact that deformation and recrystallization have not induced, but obliterated, some of the original twinning, is a direct contradiction to the concept of Emmons and Gates (1943), who believe that twinning is accentuated by external factors. It appears that twinning is a function of crystal growth, con-

trolled by the geometry of the space lattice, as proposed by Donnay. The fact that more complex types of twins are encountered in magmatic rocks is consistent with this concept.

4. The calcic feldspars show frequent compositional variations of $\pm 2\%$ within a single thin section. Larger compositional variations noticed may be attributed to chemical transformations during metamorphism and recrystallization, with consequent unmixing.

5. It is suggested that the name Indianite, proposed by Bournon in 1817, be revived and used for all natural feldspars with compositions An_{90} to An_{100} , restricting the name Anorthite to the theoretical end molecule hitherto unrecorded in nature. This will be consistent with the accepted law of nomenclature, and a recognition of Bournon's contribution to mineralogy. The classification of the plagioclase group will be as below:

0-10 % An	Albite
10-30 % An	Ologoclase
30-50 % An	Andesine
50-70 % An	Labradorite
70-90 % An	Bytownite
90-100% An	<u>Indianite</u>
100% An	Anorthite, which is the theoretical end molecule, so far not found in nature.

CLINOZOISITE

The rocks of the anorthositic series contain varying proportions of the epidote-clinozoisite group of minerals, and the following assemblages are frequently noticed:

1. Anorthite, corundum, clinozoisite
2. Anorthite, clinozoisite, garnet (grossularitic)
3. Anorthite, clinozoisite, hornblende

The more hornblendic anorthite rocks are relatively free from this mineral, while the non-hornblendic rocks carry a fair proportion of the same.

Lacroix (1889) on the basis of his optical and chemical study considered this mineral to be a dimorphic form of zoisite and called it Fouqueite, a name which has become obsolete in mineralogical nomenclature. The chemical analyses of the mineral made by Lacroix in 1889 and Chenevix in 1802 are tabulated in Table XI, while Tables XII, XIII and XIV show the chemical composition and physical properties of clinozoisite separated from rock C.39, and similar clinozoisites from elsewhere. It may be seen that the ratios of metal atoms calculated from the analysis agrees very well with the accepted empirical formula for the epidote-clinozoisite series, $H_2O.4CaO.3(AlFe)_2O_3.6SiO_2$.

In thin section the mineral occurs as rounded grains, and as anhedral and euhedral crystals, varying in size from a fifth of a millimeter to as much as five millimeters, and occasionally larger crystals are met with. Polysynthetic twinning and zoning are fairly common, as are anomalous interference colors. Johnston (1949) and Orlov (1926) have noticed a

Table XI

ANALYSES OF CLINOZOISITE FROM ANORTHITE-CORUNDUM
ROCKS OF SALEM (OF HISTORICAL INTEREST)

	1	2	3	4	5
SiO ₂	45.0	40.0	42.0	38.6	38.3
Al ₂ O ₃	28.0	25.0	25.5	32.5	31.9
Fe ₂ O ₃	11.0	11.5	14.0		
FeO				1.9	4.4
CaO	15.0	21.5	16.0	23.9	23.5
Loss on ignition	1.0	2.0	2.5	2.7	2.7
Total	100.0	100.0	100.0	99.6	100.8

1. Thallite in crystals with a rough surface. Analyst: Richard Chenevix, Phil. Trans. Roy. Soc. Lond. Vol.92, 1802, p.335.
2. Thallite in prisms like tourmaline. Analyst: Richard Chenevix (1802).
3. Thallite in fragments of a fine transparent yellow color, Analyst: Richard Chenevix (1802).
4. White Fouqueite, Analyst: A. Lacroix, Bull. Soc. Franc. de. Miner. Vol.12, 1889.
5. Yellow Fouqueite, Analyst: A Lacroix (1889).

Table XII

COMPOSITION OF CLINOZOISITE C.39

	Weight percent	Mol. ratio	Ratio O,OH,Cl	Ratio metals	Metal atoms
SiO ₂	38.64	644	1288	644	6.021)
TiO ₂	0.14	1	2	1	0.009)
Al ₂ O ₃	27.69	272	316	544	5.090)
Fe ₂ O ₃	7.57	47	141	94	0.890)
FeO	0.14	2	2	2	0.019)
MnO	0.04	-	-	-	-)
MgO	0.11	3	3	3	0.028)
CaO	23.79	424	424	424	3.964)
H ₂ O+	1.84	102	102	204	1.907)
H ₂ O-	-	-	-	-	-)
Cl	0.07	3	3	3	0.028)
O for Cl	100.03		2781	Analyst: Eileen K. Oslund and F.K.Kuroda	
	0.02		2		
	100.01		2779		

As the unit cell of epidote-clinozoisite series contains 26 (O,OH) atoms, the multiplication factor necessary to bring the oxygen ratios up to this sum would be $= \frac{26}{2.779} = 9.35$

STRUCTURAL ACCOUNT					STRUCTURE TYPE: X ₄ A ₆ B ₆ C ₆ Y ₂₆		
Ionic	ratio	X	A	B	C	Y	Electrical charges (+) (-)
Ca ²⁺	3.964		3.964				7.928
Fe	0.019		0.008	0.011			0.038
Mg	0.028		0.028				0.056
Fe ³⁺	0.890			0.890			2.670
Al	5.090			5.090			15.270
Ti ⁴⁺	0.009			0.009			0.036
Si	6.021				6.021		24.084
O ²⁻	24.065					24.065	48.130
OH ¹⁻	1.907					1.907	1.907
Cl ¹⁻	0.028					0.028	0.028
		4.00	6.00	6.021	26.00	50.082	50.065

Table XIII

MOLECULAR FORMULA AND PHYSICAL PROPERTIES OF CLINOZOISITE C.39

	R_2O_3	RO (CaO+FeO+MgO)	SiO ₂
Fe ₂ O ₃	47	63	94
Al ₂ O ₃	272	361	544
Calculated:	319	428.5	638
Actual:	319	429.0	644

14.8% of H Ca₂Fe₃Si₃O₁₃)
 85.2% of H Ca₂Al₃Si₂O₁₃) H₂O.4 (CaO+FeO+MgO).3(Al,Fe)₂O₃.6SiO₂

REFRACTIVE INDICES OF DIFFERENT MAGNETIC FRACTIONS OF C.39

Field strength	N _X	N _Y	N _Z
C.60 Amperes	1.7202 ± 001	1.7299 ± 001	1.7329 ± 001
0.65 "	1.7178 ± 001	1.7288 ± 001	1.7324 ± 001
0.70 "	1.7160 ± 001	1.7210 ± 001	1.7288 ± 001
1.00 "	1.7154 ± 001	1.7158 ± 001	1.7196 ± 001

Optic axial angle 2 V_X = 85° to 95° - (variable; sometimes 0°)

Extinction angle c ∧ X = 0° 36° (variable)

Dispersion of optic axes: variable, weak to strong

Dispersion of optic angle: r > v to r < v

Orientation: Optic plane = {001}

Elongation parallel to b axis

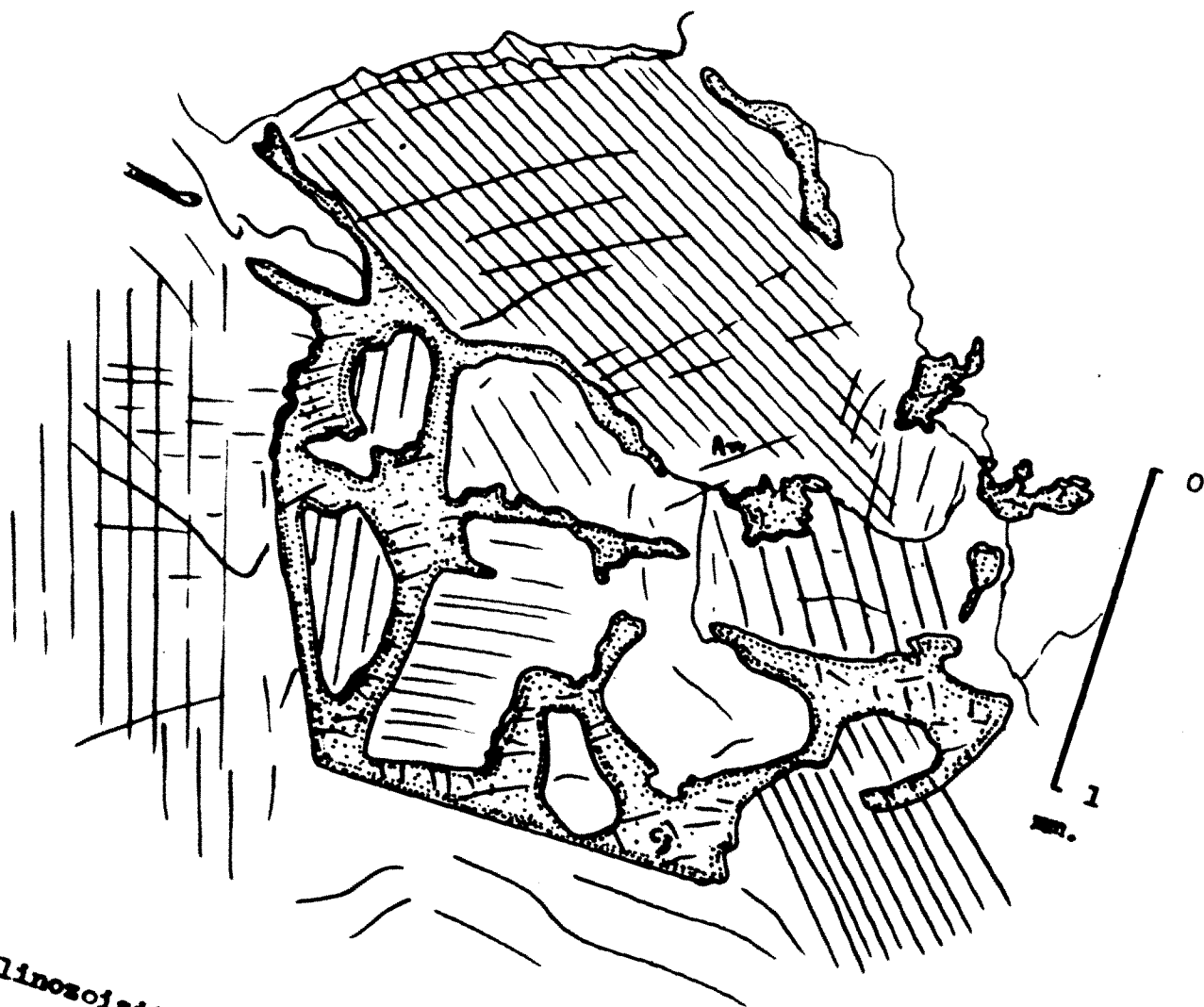
Determined Density at 28/4°C = 3390 gm/cm³

Color: In hand specimens, lemon yellow to pinkish brown, in thin section pale yellow to colorless, with very faint pleochroism.

Table XIV

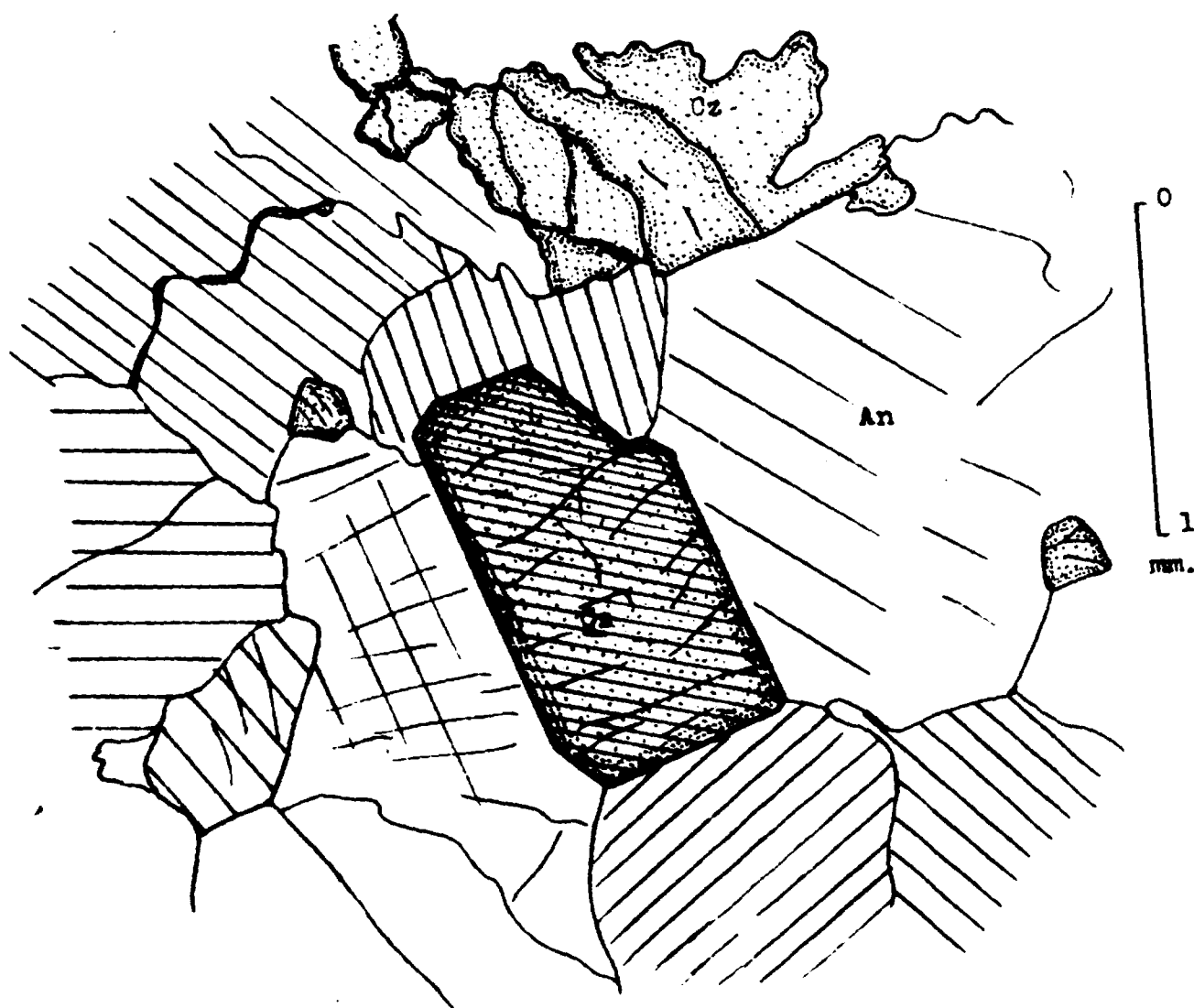
CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF SOME CLINOZOISITES

	1	2	3	4	5
SiO ₂	37.57	39.02	38.54	38.64	37.80
TiO ₂	0.18	tr	-	0.14	0.10
Al ₂ O ₃	28.20	28.64	28.39	27.69	27.63
Fe ₂ O ₃	6.61	6.81	6.89	7.57	7.62
FeO	1.87	0.34	0.50	0.14	0.19
MnO	0.12	tr	-	0.04	0.04
MgO	-	tr	tr	0.11	0.29
CaO	23.56	23.73	24.12	23.79	24.56
Na ₂ O	0.08	-	-	-	-
K ₂ O	0.01	-	-	-	-
H ₂ O+	1.93	1.76	2.26	1.84	1.83
H ₂ O-	-	-	-	-	-
Cl	-	-	-	0.07	-
				Less 0 for 0.02 Cl	
Total	100.13	100.06	100.70	100.01	100.06
Author:	H. Heritsch (1931)	H. H. Thomas (1905)	F. W. Clarke (1894)	A. P. S.	H. G. Tempel (1938)
%Total Iron as Fe ₂ O ₃	8.67	7.18	7.43	7.72 (1.7154-1.7202)	7.83
X	-	1.714	-	1.7173 (1.7158-1.7299)	1.712
Y	-	1.7196	-	1.7239 (1.7196-1.7329)	1.723
Z	-	1.725	-	1.7284	1.735
2V	-	90°-25'	-	85-95°	-
X^c	-	1°	-	0-36°	-
Density	-	3.37	-	3.390	3.324



Clinozoisite replacing anorthite in anorthite rock.

PLATE XVIII

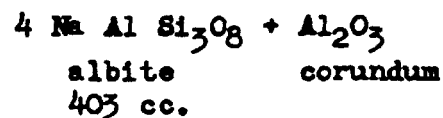
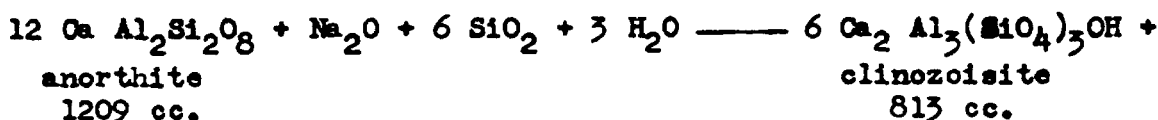
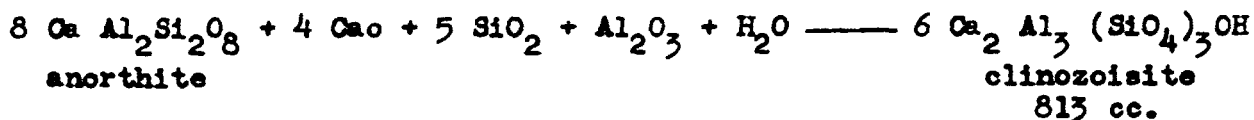


Crystal of clinozoisite in anorthite-clinozoisite gneiss

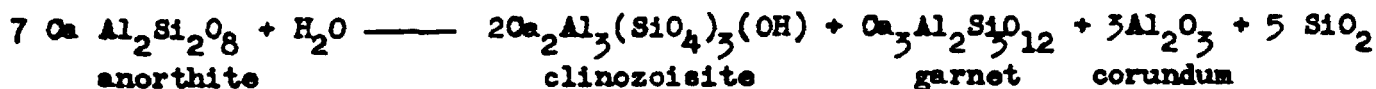
change in the dispersion of optic axes, and the former has indicated a relationship between the extinction angle and optic angle. In the present instance the change in dispersion and a wide variation in the optic angle and extinction angle have been noticed.

The composition changes in a single specimen of the mineral isolated from one rock are indicated by the variation in refractive indices for different magnetic fractions as shown in Table X. The composition range of this mineral in the rocks studied, on the basis of index determinations, is from 5 to 30% of epidote molecule. In a few cases grains with extinction angles larger than 45° have been noticed, which, according to Orlov (1926), should be β clinozoisite.

The following equations suggested by Turner (1948) may indicate the general trend of chemical reactions leading to the formation of this mineral:



The following equation has been suggested earlier for the garnet-clinozoisite-corundum paragenesis:



Johnstone (1949) has stated that when the iron content is low temperatures and pressures prevailing during the period of crystallization may influence the optics of clinozoisite. The wide variation in optical properties of the clinozoisites under study warrants concurrence with Johnstone's view.

CORDIERITE

Cordierite is an essential mineral in a peculiar assemblage composed of anorthite, corundum, cordierite, anthophyllite and sillimanite which occurs as an inclusion in the anorthositic rocks.

The mineral is readily identified in hand specimens by its blue color and greasy luster, and occurs as shapeless grains of varying sizes in a matrix of corundum and anorthite. In thin section the mineral is distinguished from anorthite by its lower indices of refraction and by the presence of aggregates of acicular sillimanite. Inclusions of anthophyllite are also noticed. Pleochroic haloes commonly found in cordierite are not seen. The presence of these inclusions which vary in size from acicular crystals to dusty particles impart a cloudy appearance to the mineral in thin section. The mineral is unusually fresh and alteration to pinite is rarely encountered. Pleochroism is not noticeable, thereby indicating it to be an iron poor, magnesia rich variety. Occasionally the mineral displays lamellar twinning of a 'pseudo Baveno' type, simulating plagioclase feldspar. The pole of the composition plane when plotted on a stereogram and transposed on the composition curves for plagioclase feldspars falls on the 'Baveno' curve, a feature recorded in cordierites from South Africa by Willemse (1937) and Brink (1950). This

COMPOSITION OF CORDIERITE C.71

	Weight percent	Mol. ratio	Ratio O,OH,	Ratio metals	Metal atoms
SiO ₂	49.54	825	1650	825	4.859
TiO ₂	0.03	-	-	-	-
Al ₂ O ₃	33.42	328	984	656	3.863
Fe ₂ O ₃	0.14	1	3	2	0.012
FeO	3.75	52	52	52	0.306
MnO	0.09	1	1	1	0.006
MgO	11.34	281	281	281	1.655
CaO	0.10	2	2	2	0.012
Na ₂ O	0.32	10	10	20	0.120
K ₂ O	0.01	-	-	-	-
H ₂ O+	1.32	73	73	146	0.860
H ₂ O-	0.03	-	-	-	-
F	0.01	-	-	-	-
Cl	0.00	-	-	-	-

100.10

3056 Analyst: Eileen K. Oslund

The unit cell of cordierite contains 18 (O,OH) atoms, and the multiplication factor necessary to bring the oxygen ratios up to this would be:

$$\frac{18}{3.056} = 5.89$$

STRUCTURAL ACCOUNT				STRUCTURE TYPE = X ₀ A ₂ B ₄ C ₅ Y ₁₈			
Ionic	ratio	X	A	B	C	Y	Electrical charges (+) (-)
K ¹⁺	-						
Na	0.120			0.120			0.120
Ca ²⁺	0.012		0.012				0.024
Mn	0.006		0.006				0.012
Fe	0.306		0.306				0.612
Mg	1.655		1.655				3.310
Fe ³⁺	0.012			0.012			0.036
Al	3.863			3.863			11.589
Ti ⁴⁺	-						
Si	4.859				4.859		19.436
O ²⁻	17.14					17.14	34.28
OH ¹⁻	0.86					0.86	0.86
		1.979	3.995	4.859	13.00	35.139	35.14

Table XVI

COMPOSITION AND PHYSICAL PROPERTIES OF SOME MAGNESIAN CORDIERITES

Number:	1	2	3	4	5	6	7	8
Author:	Fehrman	Tilley	Subra- maniam	Oppenheimer	Thiele	Oppen- heimer	Thiele	Duparc
Locality:	Attu	Antarctica	India	Tvedestrand		Bodenmais	Orjarvi	Tsila-
SiO ₂	50.15	47.96	49.54	49.18	48.05	48.53	49.60	49.05
TiO ₂	0.38	0.00	0.03	-	-	-	-	-
Al ₂ O ₃	33.07	31.56	33.42	32.28	33.37	31.47	31.19	33.08
Fe ₂ O ₃	1.52	1.03	0.14	1.08	0.09	1.35	1.19	0.83
FeO	2.22	3.24	3.75	4.05	4.01	4.30	4.10	4.38
MnO	0.12	1.09	0.09	-	tr	-	-	-
MgO	11.01	12.16	11.34	11.35	11.11	10.68	11.13	11.04
CaO	0.29	0.00	0.10	-	0.05	tr	0.23	-
Na ₂ O	0.14	0.33	0.32	0.65	0.26	0.35	0.21	-
K ₂ O	0.08	tr	0.01	-	0.39	-	0.06	-
H ₂ O+	1.37	2.30	1.32	2.04	2.75	1.82	2.33	1.64
H ₂ O-	0.09	n.d.	0.03	0.27	-	0.14	0.08	-
F ⁻	-	-	0.01	-	-	-	-	-
	100.44	100.17	100.10	99.80	100.08	99.79	100.22	100.02
Percentage of Mg ₂ Al ₄ Si ₅ O ₁₈	84.3	84.2	83.6	83.0	32.9	81.6	79.5	78.6
Analyst:	Fehrman	A.F. White	E.K. Colund	Dittrich	Thiele	Dittrich	Thiele	Duparc
Density	2.588	-	2.591	2.581	2.531	2.603	2.598	2.593
N _X	1.527	1.534	1.5392	1.5358	1.536	1.5400	1.541	1.5395
N _Y	1.532	-	1.5438	1.5406	-	1.5460	1.545	1.5448
N _Z	1.538	1.543	1.5462	1.5428	1.543	1.5486	1.547	1.5475
2V	88°	76°	66±2°	69°26'	65°36'	65°36'	78°12'	72°37'
Optic sign	+	+	-	-	-	-	-	-
Parent rock	Anthophyl- lite gneiss	Gneiss	Cordierite Corundum Anthophyl- lite rock	Gneiss	Gneiss	Gneiss	Gneiss	Mica- schist

Table XVII

COMPOSITION AND OPTICAL PROPERTIES OF CORDIERITE C.71

	<u>RO</u>	<u>Al₂O₃</u>	<u>SiO₂</u>
MgO	140.5	231	702.5
FeO	26	52	130
MnO	0.5	1	2.5
Fe ₂ O ₃	1	2	5.0
Calculated	168	336	840.0
Actual	168	328	825.0

83.6 % Mg₂ Al₄ Si₅ O₁₈

16.4 % (Fe,Mn)₂ Al₄ Si₅ O₁₈

Determined Density at 27/4°C = 2.591 gm/cm³

Refractive Indices in Sodium light:

$$N_X = 1.5392 \pm .0005$$

$$N_Y = 1.5438 \pm .0005$$

$$N_Z = 1.5462 \pm .0005$$

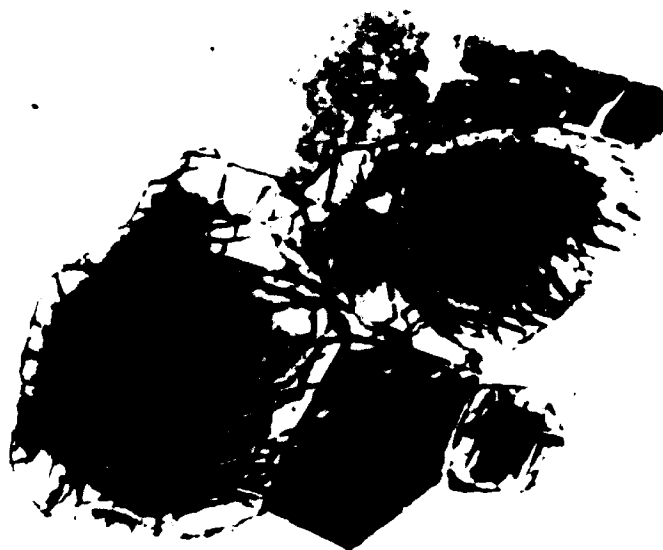
Optic Axial Angle 2V in Sodium light = 64, 64.5, 65, 66, 67, 68, 69, 70.

General value 66 ± 2°, fairly consistent.

Dispersion of optic angle = r < v weak.

Inclusions of sillimanite and anthophyllite noticed in abundance in thin sections.

Color: In fragments grayish blue to dark blue, in translucent chips pale blue, in 80 mesh lilac blue, in thin section very pale blue to colorless and non-pleochroic.



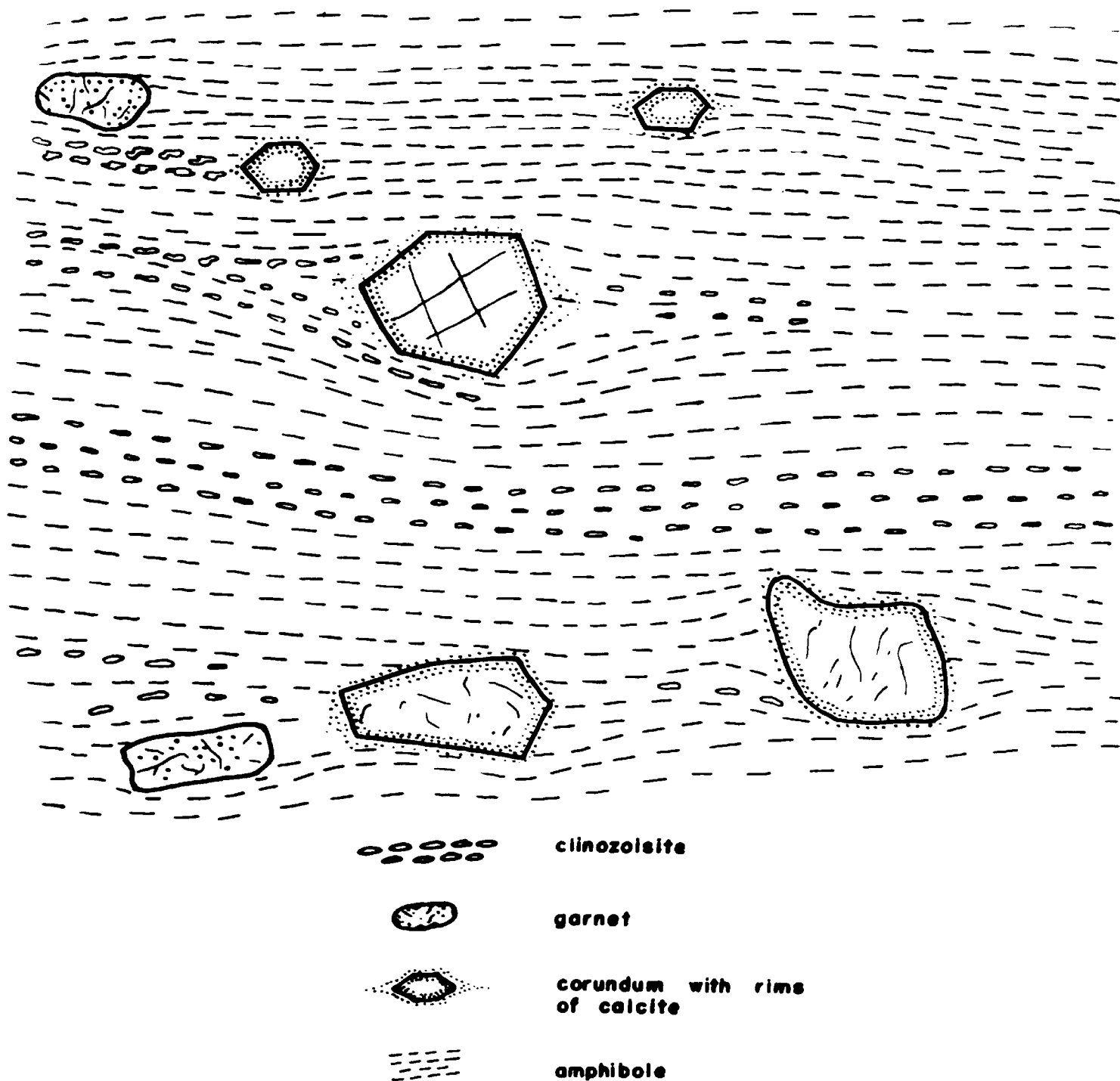
Clinozoisite crystals displaying strong zoning X . 50



Cordierite displaying lamellar twinning. Note dusty
inclusions in the mineral.
X. 100

PLATE XX

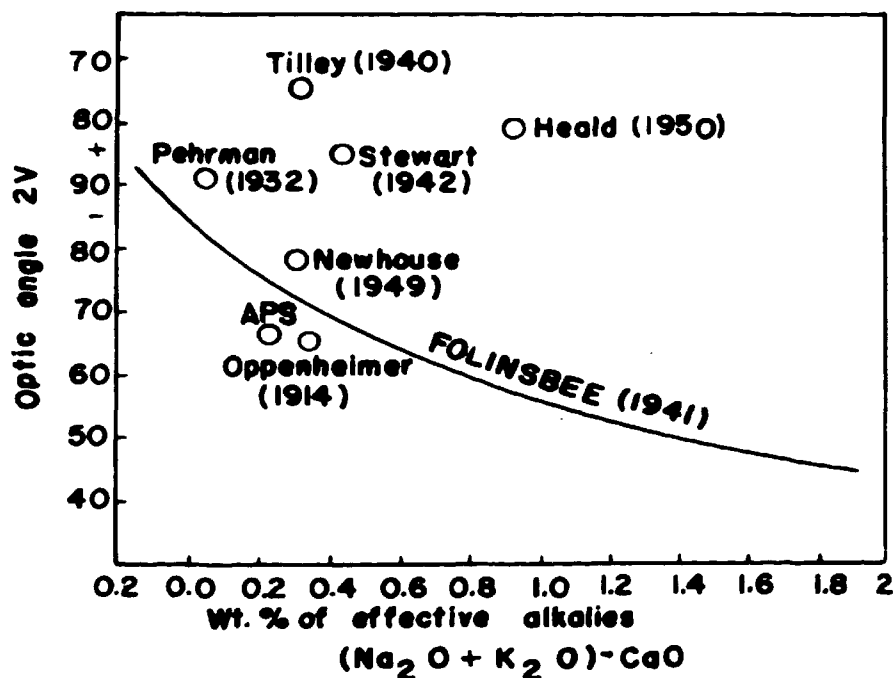
Sketch showing, corundum, clinozoisite, garnet, anorthite paragenesis on the foot-wall of corundum quarry south of Sittampundi. Note hornblende and clinozoisite wrapping around the corundum crystals



feature may be of significance in establishing a migration curve of the poles of composition planes for cordierites of varying composition which may prove useful for diagnostic purposes.

The chemical composition of this cordierite is shown in Table XV and the composition and physical properties of some magnesian cordierites are shown in Table XVI. The calculation of the molecular formula of the mineral after the method of Winchell (1937), and its physical and optical properties, are shown in Table XVIII.

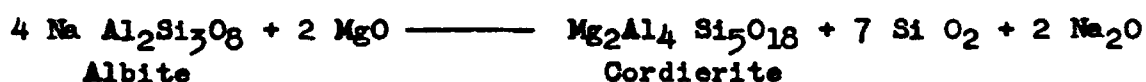
The optical properties of cordierite have been investigated by several workers all over the world in view of the mineral exhibiting anomalous optical characters. Various attempts have been made to relate these anomalous characters with the chemical composition, Krishnan (1924), Pehrman (1932), Shibata (1936), Winchell (1937), Thiele (1940) and Folinsbee (1941). Folinsbee has suggested that the alkalies and lime play an important role in determining the size of the optic angle and the sign of the mineral and considered the size of the optic angle of cordierite to be a function of effective alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$). Four analyses of cordierite published since then, and the present one, do not fit in with this concept, as also some of the older analyses of Oppenheimer (1914) and Pehrman (1932). An inspection of Table VII will show that the positive cordierites are not different chemically from the negative ones.



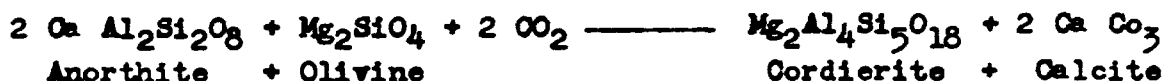
Thiele (1940) has discussed the effects of water content and isomorphous substitution of Si and Mg for Al on the optical properties of cordierite and an attempt was made by the writer to correlate the chemistry and optics of cordierites found in literature, but nothing satisfactory could be evolved due to the paucity of precise data. While agreeing with Stewart (1942) and Heald (1950) that sufficient data are not available to establish specific relationships between the chemical and optical characters of cordierite, available information in the literature leads the writer to suspect that these optical anomalies may be due to peculiarities in the distribution of the ions in the cordierite structure. It would be necessary to carry out statistical x-ray analyses of positive

and negative cordierites to evaluate the merits of this suggestion. It is improbable that the thermal history has anything to do with the optical peculiarities of cordierite as it is mostly found in metamorphic assemblages, and nothing peculiar has been observed in cordierites found in slags and rocks formed at higher temperatures.

Paragenesis: The mineral makes up nearly 30% of a rock containing almost an equal proportion of corundum and calcic plagioclase, and thought to be an inclusion in the anorthosite. Thomas (1922) has described an identical paragenesis in xenoliths in Mill. He considers them to be modifications of pure aluminous sediment by permeation of magmatic matter, and the diffusion of lime, ferrous iron and magnesia. He ascribes the formation of cordierite to relative enrichment of such xenoliths in magnesia and alkalis, with concomittant separation of corundum, spinel and acid plagioclase. Bugge (1943) has advocated a metasomatic origin for cordierite suggesting the following equations:



The following modification of Bugge's second equation is thought to have been operative in the present instance:



The presence of calcite and scapolite in the cordierite rock is indicative of some reaction similar to one shown in a simplified form above.

ANTHOPHYLLITE

Anthophyllite occurs in some of the anorthositic rocks and in most of the chromitites, as honey-brown colored prismatic crystals, varying from a millimeter to as much as ten centimeters in length, in close association with monoclinic amphiboles. In some of the chromitites the bladed crystals of the mineral display an unusual play of colors, which may be due to the microscopic inclusions of chrome spinel noticed in thin sections.

The chemical composition of the mineral and the probable distribution of the various ions are presented in Table XVIII. The analyzed anthophyllite is exceptionally rich in alumina and magnesia, and is similar to anthophyllite from Mason's Creek, described and analyzed by Henderson (1931). This, according to Rabbitt (1948), is an aluminian anthophyllite, or according to Berman (1937), Winchell (1938), Tilley (1939), Sundius (1944), and Eskola (1950), gedrite. Rabbitt (1948) has proposed, without any specific reasons, that the name gedrite be dropped. It appears to the writer more reasonable to retain the name gedrite, as according to Sundius (1944) anthophyllite-gedrite represents one of the several isomorphous series in the amphibole group. Rabbitt has presented a curve, expressing relationship between N_z and the weight percentage of $(FeO + Fe_2O_3 + MnO + TiO_2)$. The refractive index N_z of the analyzed anthophyllite does not fit Rabbitt's curve. This may be attributed to the high alumina content of the analyzed mineral, as the more aluminian anthophyllites used by Rabbitt generally show points for N_z above the curve. This distinctive optical character of the aluminian variety warrants retention of the name gedrite.

COMPOSITION OF ANTHOPHYLLITE C.58

	Weight percent	Mol. ratio	Ratio O,CH,F,Cl	Ratio metals	Metal atoms
SiO ₂	45.50	757	1514	757	6.330
TiO ₂	0.23	3	6	3	0.025
Al ₂ O ₃	17.64	173	519	346	2.890
Fe ₂ O ₃	2.16	13.5	41	27	0.220
FeO	9.04	126	126	126	1.050
MnO	0.16	2	2	2	0.017
MgO	20.51	508	508	508	4.240
CaO	0.87	15	15	15	0.120
Na ₂ O	1.73	28	28	56	0.470
K ₂ O	0.00	-	-	-	-
H ₂ O+	2.12	117	117	234	1.95
H ₂ O-	0.09	-	-	-	-
Cl	0.05	2	2	2	0.017
F	0.02	1	1	1	0.008

100.12

2879

O for Cl
and F

0.02

2

100.10

2877

Analyst: S. S. Goldich

Multiplication factor to build 24 (O,OH) atoms in unit cell = $\frac{24}{2.877} = 8.35$

STRUCTURAL ACCOUNT

STRUCTURE TYPE: (X+A+B)₇ C₈ Y₂₄

Ionic	ratio	X	A	B	C	Y	Electrical (+)	charges (-)
K ¹⁺	0.00							
Na	0.47	0.47					0.47	
Ca ²⁺	0.12		0.12				0.24	
Mn	0.017		0.017				0.034	
Fe	1.05		1.05				2.10	
Mg	4.24			4.24			8.48	
Fe ³⁺	0.22			0.22			0.22	
Al	2.890			1.22	1.67		8.67	
Ti ⁴⁺	0.025			0.025			0.100	
Si	6.330				6.33		25.320	
O ²⁻	22.025					22.025		44.050
OH ¹⁻	1.950					1.950		1.950
Cl ¹⁻	0.017					0.017		0.017
F ¹⁻	0.008					0.008		0.008
		0.47	1.187	5.705	8.00	24.00	46.074	46.025

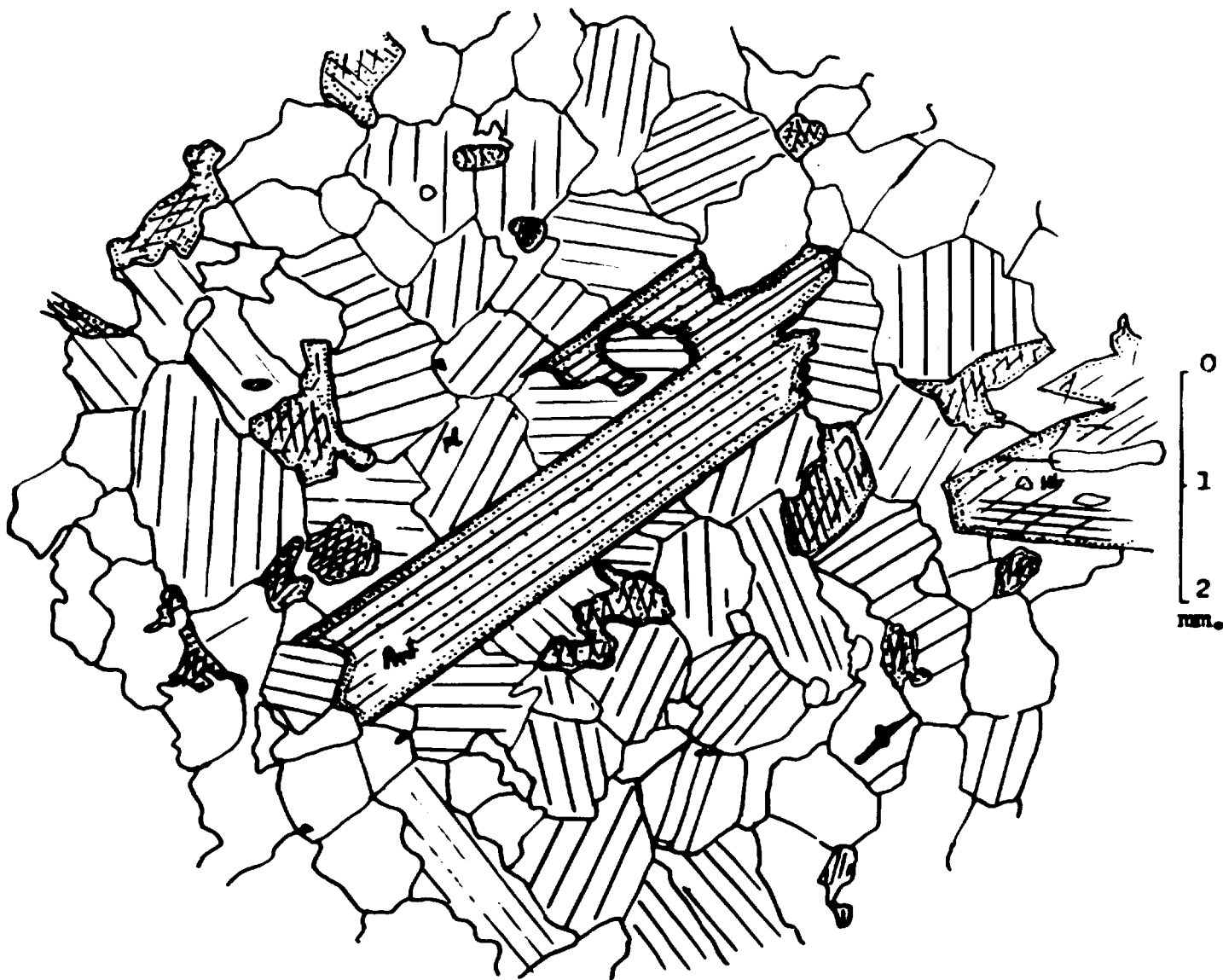


Bladed crystal of anthophyllite in anorthosite. X 9



Bladed crystal of anthophyllite in chromitite. Note inclusions of chromite and spinel in the anthophyllite.

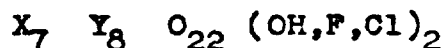
X. 10



Anthophyllite in anorthite-anthophyllite -hornblende rock.

**Note the sub-hedral anorthite crystals giving the
rock a mosaic texture, in thin section**

The following general formula has been proposed for the anthophyllite series by Rabbitt:

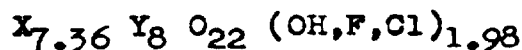


where X is mainly Mg, Fe²⁺, Al and in minor part Mn, Ti, Fe³⁺, Ca, Na and K, and Y mostly Si with part replacement by Al.

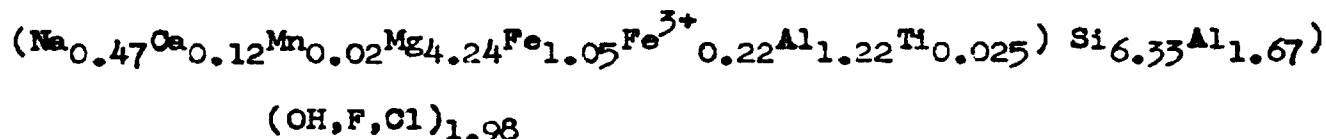
Berman (1937) proposed the following formula for gedrite:



In the present instance the following formula is indicated by the chemical analysis:



or



The above formula is in accordance with those proposed by Berman and Rabbitt.

The physical properties of the analyzed specimen are tabulated below:

$$N_X = 1.6415 \pm .0005$$

$$N_Y = 1.6494 \pm .0005$$

$$N_Z = 1.6578 \pm .0005$$

$$\text{Birefringence, } N_g - N_X = 0.0163$$

$$\text{Optical Axial angle } 2V = +88 \pm 2^\circ$$

$$\text{Orientation: } Z = c \quad Y = b$$

$$\text{Elongation: } \text{Positive}$$

$$\begin{aligned} \text{Absorption: } & X = Y \quad Z \\ & X = \text{Pale tan grey} \\ & Y = \text{Pale tan grey} \\ & Z = \text{Tan grey to clove brown} \end{aligned}$$

Dispersion: weak

Density at 26/4°C = 3.164 gm/cm³

The anthophyllite from some of the chromitites have much lower values for N_z , as shown below, which may be due to their having a more magnesian composition.

C.94 $N_z = 1.6372 \pm .0005$

C.72 $N_z = 1.6436 \pm .0005$

CLINO-AMPHIBOLES

Monoclinic amphibole is the prevalent mafic mineral in the anorthositic rocks and chromitites. The eclogitic gabbros also contain a fair amount of the mineral, commonly replacing pyroxene. The amphibole in the anorthositic rocks occurs as prismatic and acicular crystals one-half to four millimeters in length with their longer axes parallel to each other, imparting a lineation to the rocks. These rocks contain from five to ninety per cent of amphiboles, the more mafic concentrations occurring as layers within the anorthosites. The amphibole in the chromitite has a bright green color ranging in size from 0.5 to 5. mm., and makes up twenty to ninety per cent of the rock depending on the chromite content. These amphiboles also occur as prismatic and acicular crystals and impart a lineation to the rocks by their preferred orientation. These two varieties of amphibole were separated and chemically analyzed in view of their having different optical characters.

The chemical analyses of the two amphiboles and the probable distribution of ions are presented in Tables XIX and XX. Tables XXI and XXII show the chemical composition of an amphibole as recalculated from the rock analysis. In Table XXIII the distribution of the ions in the above three analyses, according to Sundius (1946), are shown, which indicate the

COMPOSITION OF AMPHIBOLE C.34

	Weight percent	Mol. ratio	Ratio C, OH, F, Cl	Ratio metals	Metal atoms
SiO ₂	42.32	705	1410	705	6.330
TiO ₂	0.27	4	8	4	0.035
Al ₂ O ₃	15.62	153	459	306	2.662
Fe ₂ O ₃	4.22	26	78	52	0.452
Cr ₂ O ₃	0.06	-	-	-	-
FeO	6.78	94	94	94	0.818
MnO	0.15	2	2	2	0.017
MgO	13.68	339	339	339	2.950
CaO	11.78	210	210	210	1.830
Na ₂ O	2.41	39	39	78	0.678
K ₂ O	0.34	3	3	6	0.052
H ₂ O+	2.13	118	118	236	2.053
H ₂ O-	0.11	-	-	-	-
Cl	0.03	1	1	1	0.008
F	0.02	1	1	1	0.008
O for Cl & F	99.92		2762	Analyst: Eileen K. Oslund Halogens by P.K. Kuroda	
	0.02		1		
	99.90		2761		

Multiplication factor to build 24 (O,OH) atoms in unit cell = $\frac{24}{2.761} = 8.70$

STRUCTURAL ACCOUNT			STRUCTURE TYPE: X ₀₋₁ A ₂ B ₅ C ₈ Y ₂₄					
Ionic	Ratio	X	A	B	C	Y	Electrical charges (+) (-)	
K ¹⁺	0.052	0.052					0.052	
Na	0.678	0.678					0.678	
Ca ²⁺	1.830	0.094	1.736				3.660	
Mn	0.017		0.017				0.034	
Fe	0.818		0.247	0.571			1.636	
Mg	2.950			2.950			5.900	
Fe ³⁺	0.452			0.452			1.356	
Al	2.662			0.992	1.670		7.986	
Cr	-			-			-	
Ti ⁴⁺	0.035			0.035			0.140	
Si	6.330				6.330		25.320	
O ²⁻	21.931					21.931		43.862
OH ¹⁻	2.053					2.053		2.053
Cl ¹⁻	0.008					0.008		0.008
F ¹⁻	0.008					0.008		0.008
		0.824	2.00	5.00	8.00	24.00	46.762	45.931

COMPOSITION OF AMPHIBOLE C.70

	Weight percent	Mol. ratio	Ratio O, OH, F, Cl	Ratio metals	Metal atoms			
SiO ₂	44.96	749	1498	749	6.381			
TiO ₂	0.23	3	6	3	0.025			
Al ₂ O ₃	14.90	146	438	292	2.487			
Fe ₂ O ₃	1.51	9.5	28	19	0.162			
Cr ₂ O ₃	1.92	12.5	38	25	0.213			
FeO	4.05	56	56	56	0.477			
MnO	0.09	1	1	1	0.008			
MgO	16.05	398	398	398	3.391			
CaO	11.92	212	212	212	1.806			
Na ₂ O	1.51	24	24	48	0.409			
K ₂ O	0.12	1	1	2	0.017			
H ₂ O ⁺	2.26	126	126	252	2.147			
H ₂ O ⁻	0.15	-	-	-	-			
Cl ⁻	0.05	2	2	2	0.017			
F ⁻	0.02	1	1	1	0.008			
O for Cl & F	99.74 <u>0.02</u> 99.72		2829 <u>2</u> 2827	Analyst: Eileen K. Oslund Halogens by P.K. Kuroda				
Multiplication factor to build 24 (O, OH) in unit cell = $\frac{24}{2827} = 8.52$								
STRUCTURAL ACCOUNT			STRUCTURE TYPE: X ₀₋₁ A ₂ B ₅ C ₈ Y ₂₄					
Ionic	Ratio	X	A	B	C	Y	Electrical charges (+)	(-)
K ¹⁺	0.017	0.017					0.017	
Na	0.409	0.409					0.409	
Ca ²⁺	1.806		1.806				3.612	
Mn	0.008		0.008				0.016	
Fe	0.477		0.186	0.291			0.954	
Mg	3.391			3.391			6.782	
Fe ³⁺	0.162			0.162			0.486	
Al	2.487			0.868	1.619		7.461	
Cr	0.213			0.213			0.639	
Ti ⁴⁺	0.025			0.025			0.100	
Si	6.381				6.381		25.524	
O ²⁻	21.328					21.328		43.656
OH ¹⁻	2.147					2.147		2.147
Cl ¹⁻	0.017					0.017		0.017
F ¹⁻	0.008					0.008		0.008
		0.426	2.00	4.950	8.00	24.00	46.00	45.828

Table XXI

COMPOSITION OF AMPHIBOLE FROM ROCK C.33,
WITH 79% OF ANORTHITE, AND 21% OF AMPHIBOLE BY WEIGHT.
COMPOSITION OF ANORTHITE FIXED ON THE BASIS OF
SPECTROSCOPIC AND OPTICAL DATA.

	Weight % in rock	Weight % in 79% of plagioclase An ₉₀	Weight % in rock after deducting feldspar	Composition of Amphibole recalculated
SiO ₂	44.58	36.14	8.44	40.19
TiO ₂	0.06	-	0.06	0.28
Al ₂ O ₃	30.81	27.63	3.18	15.14
Fe ₂ O ₃	0.94	-	0.94	4.47
Cr ₂ O ₃	0.02	-	0.02	0.09
FeO	1.77	-	1.77	8.41
MnO	0.04	-	0.04	0.18
MgO	2.72	-	2.72	12.95
CaO	17.05	14.21	2.84	13.50
Na ₂ O	1.35	0.93	0.42	2.00
K ₂ O	0.07	-	0.07	0.33
H ₂ O+	0.58	0.14*	0.44	2.09
H ₂ O-	0.06	-	0.06	0.28
Cl	0.01	-	0.01	0.04
F	0.01	-	0.01	0.04
Less O for Cl & F	0.01			0.02
Total:	100.06			99.97

*Analysis of feldspar from similar rocks indicated combined H₂O in them and hence a proportionate amount has been allotted.

COMPOSITION OF AMPHIBOLE C.33

	Weight percent	Mol. ratio	Ratio O,CH,F,Cl	Ratio metals	Metal atoms
SiO ₂	40.19	669	1338	669	5.920
TiO ₂	0.28	4	8	4	0.036
Al ₂ O ₃	15.14	148	444	296	2.619
Fe ₂ O ₃	4.47	28	84	56	0.495
Cr ₂ O ₃	0.09	1	3	2	0.018
FeO	3.41	117	117	117	1.035
MnO	0.18	3	3	3	0.027
MgO	12.95	321	321	321	2.841
CaO	13.50	241	241	241	2.132
Na ₂ O	2.00	32	32	64	0.566
K ₂ O	0.33	3	3	6	0.054
H ₂ O+	2.09	116	116	232	2.053
H ₂ O-	0.28	-	-	-	-
Cl	0.04	2	2	2	0.018
F	0.04	2	2	2	0.018
	99.71		2714		
O for Cl & f	<u>0.02</u>		<u>2</u>		
	99.69		2712	Analyst: Eileen K. Oslund	

Multiplication factor to build 24 (O,OH) atoms in unit cell = $\frac{24}{2.712} = 8.85$

STRUCTURAL ACCOUNT			STRUCTURE TYPE: X ₀₋₁ A ₂ B ₅ C ₈ Y ₂₄				
Ionic	Ratio	X	A	B	C	Y	Electrical charges (+)(-)
K ¹⁺	0.054	0.054					0.054
Na	0.566	0.566					0.566
Ca ²⁺	2.132	0.123	2.00	0.009			4.264
Mn	0.027			0.027			0.054
Fe	1.035			1.035			2.070
Mg	2.841			2.841			5.682
Fe ³⁺	0.495			0.495			1.485
Al	2.619			0.539	2.080		7.357
Cr	0.018			0.018			0.054
Ti ⁴⁺	0.036			0.036			
Si	5.920				5.920		23.680
O ²⁻	21.911					21.911	43.822
OH ¹⁻	2.053					2.053	2.053
Cl ¹⁻	0.018					0.018	0.018
F ¹⁻	0.018					0.018	0.018
		0.743	2.00	5.00	8.00	24.00	45.910
							45.911

STRUCTURAL ACCOUNT OF THE ANALYZED AMPHIBOLES AFTER SUNDIUS (1946)
INDICATING AFFINITIES TO THE EDENITE AND PARGASITE TYPE

Ions	Amphibole C.34				Amphibole C.33 (calculated)			
	Distribution of ions after Sundius (1946)				Type formula for Edenite	Distribution of ions after Sundius (1946)		
Si	6.330					(		5.920
Al	2.662	0.670	7	7	7	(	1.080	
		1.00	1	1	1	(	1.00	2.619
		0.992				(	0.539	
Fe ³⁺	0.452					(		0.495
Ti	0.035					(		0.036
Fe ²⁺	0.818		5.264	5	4.973	(		1.035
Mg	2.950					(		2.841
Mn	0.017					(		0.027
Ca	1.830		1.830	2	2.132			2.132
Na	0.678					(		0.566
K	0.052		0.730	1	0.620	(		0.054
OH	2.053					(		2.053
Cl	0.008		2.069	2	2.089	(		0.018
F	0.008					(		0.018

Ions	Amphibole C.70			
	Distribution of ions after Sundius (1946)		Type formula for Pargasite	
Si	6.381	6.381	6	
Al	2.487	2	2	
Fe ³⁺	0.162	.487 } .649	1	
Ti	0.025			
Fe ²⁺	0.477			
Mg	3.391	3.901	4	
Mn	0.008			
Ca	1.806	1.806	2	
Na	0.409			
K	0.017	0.426	1	
OH	2.147			
Cl	0.017	2.172	2	
F	0.008			

- 79 -
Table XXIV

OPTICAL AND PHYSICAL PROPERTIES OF ANALYZED AMPHIBOLES

	C.34	C.70
N_X	$1.6506 \pm .0005$	$1.6402 \pm .0005$
N_Y	$1.6611 \pm .0005$	$1.6473 \pm .0005$
N_Z	$1.6688 \pm .0005$	$1.6565 \pm .0005$
$\angle AZ$	$16^\circ \pm 1^\circ$	$19^\circ \pm 1^\circ$
$2 V$	$-83.5^\circ \pm 2^\circ$	$+85.5^\circ \pm 2^\circ$
Dispersion of optic angle	$r < v$	$r > v$
Dispersion	weak	weak
Absorption	$X < Y < Z$	$X = Y < Z$
X	Pale yellowish green	Pale green
Y	Pale green	Pale green
Z	Bluish green	Emerald green
Orientation	Optic plane $11\{010\}$	Optic plane $11\{010\}$
Elongation	Positive	Positive
Cleavage	Well developed (110)	Well developed (110)
Parting	Distinct (010)	Distinct (010)
Twinning	Rare	Rare
Habit	Long prismatic and acicular crystals	Long prismatic and acicular crystals
Size	1 mm to 5 cms	1 mm to 5 cms
Color in hand specimens	Greenish black to black	Emerald green to dark green
Density at 26/4°C	3.167 gm/cm^3	3.117 gm/cm^3

Table XXV

OPTICAL PROPERTIES OF SOME AMPHIBOLES

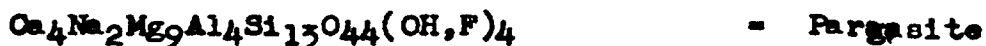
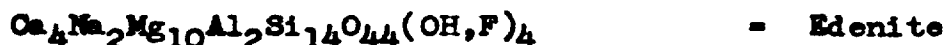
	C.33	C.128
N_X	$1.6517 \pm .0005$	$1.6572 \pm .0005$
N_Y	$1.6614 \pm .0005$	$1.6695 \pm .0005$
N_Z	$1.6694 \pm .0005$	$1.6792 \pm .0005$
2V	$-84^\circ \pm 1^\circ$	$-79.5^\circ \pm 1^\circ$
$c \wedge Z$	$17^\circ \pm 1^\circ$	$18^\circ \pm 1^\circ$
Dispersion of optic angle	$r < v$	$r < v$
Dispersion	Weak	Weak
Absorption	$X < Y < Z$	$X < Y < Z$
X	Yellowish green	Yellowish green
Y	Pale green	Pale green
Z	Bluish green	Bluish green

No.	N_X	N_Y	N_Z	2V	Absorption
C.47	1.639	1.647	1.657	+85	$X = Y < Z$
C.94	1.639	1.648	1.658	+85	$X = Y < Z$
C.101	1.639	1.648	1.658	+86	$X = Y < Z$
C.4	1.649	1.658	1.667	-82	$X < Y < Z$
C.15	1.651	1.661	1.669	-83	$X < Y < Z$
C.84	1.651	1.661	1.669	-83	$X < Y < Z$
C.53	1.653	1.663	1.671	-81	$X < Y < Z$
C.69	1.649	1.659	1.667	-84	$X < Y < Z$
C.96	1.651	1.660	1.668	-82	$X < Y < Z$
C.120	1.650	1.658	1.668	-82	$X < Y < Z$

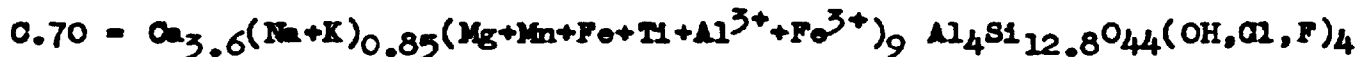
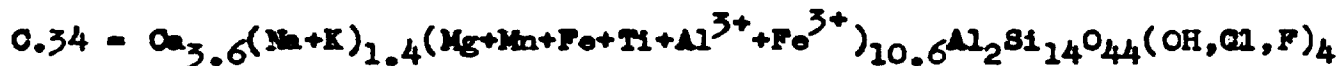
Note: All index measurements $\pm .002$, and 2 V measurements $\pm 1^\circ$

affinitites of these amphiboles to edenite and paragsite. The physical and optical properties of the analyzed specimens and the optical properties of some others from the various rocks are tabulated in Tables XXIV and XXV. Plate 9 shows curves relating the chemical composition with the principal optical properties.

Important discussions have appeared in recent years on the chemical and optical properties of monoclinic amphiboles, Hallimond (1943), Winchell (1945), Foslie (1945) and Sundius (1946). The most important contribution is by Sundius who has presented a classification of the monoclinic amphiboles on the basis of their chemistry. According to him the Si content in the calciferous amphiboles is always less than eight, with substitutions of Na Al for Si and Al Al for Mg Si, as a characteristic feature. The type formulas arising out of such substitutions are $\text{NaCa}_2\text{Mg}_5\text{AlSi}_7\text{O}_{22}(\text{OH})_2$ = edenite, $\text{NaCa}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{22}(\text{OH})_2$ = pargasite, and $\text{Ca}_2\text{Mg}_3\text{Al}_1\text{Si}_6\text{O}_{22}(\text{OH})_2$ = Tschermakite. Berman (1937) gives the following structural formula for edenite and pargasite.



The formula indicated by the analyzed amphiboles are:



It may be noted that the formula of Berman for pargasite is different from that of Sundius in containing more magnesia and less aluminum. However, the present analyses fits in very well with Berman's formula, except

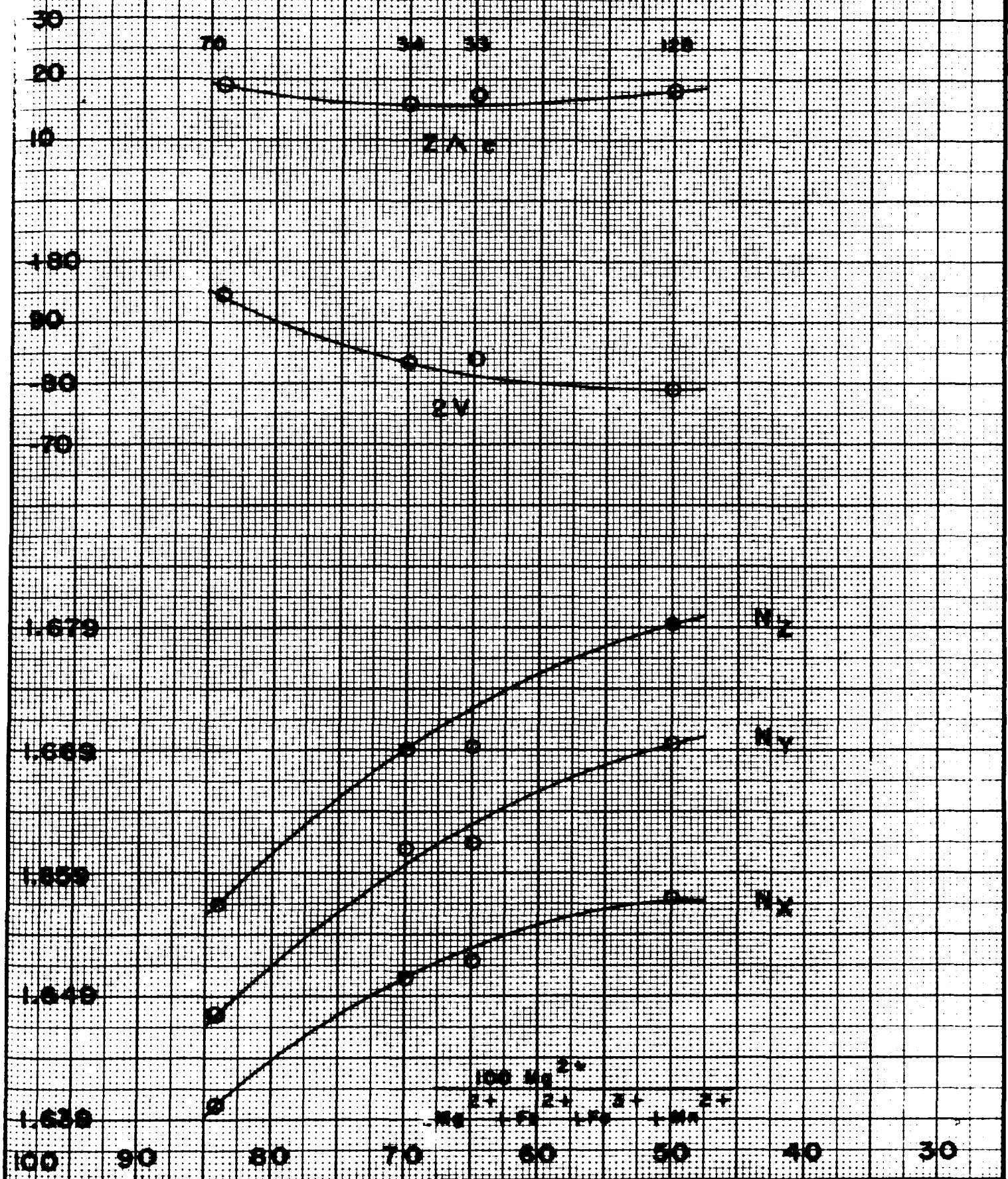
for deficiency in lime and alkalies. In any case, the chemical compositions of the analyzed amphiboles approach edenite and pargasite respectively. The optical properties of these amphiboles are variable within a single thin section, particularly the optic angle and extinction angle. The extinction angles and optic axial angles used for the curves represent the average of over a hundred determinations.

The amphiboles analyzed have the following normative composition:

	<u>C.34</u>	<u>C.70</u>
Or	1.67	0.56
Ab	4.72	12.58
Ne	8.52	-
An	31.69	33.64
Di	21.52	22.22
Ol	23.27	24.71
Mt	6.03	2.09
Il	0.61	0.46
Cr	-	2.91

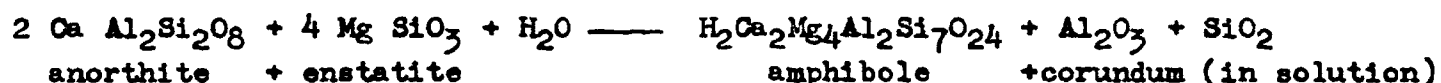
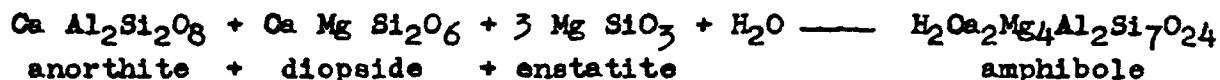
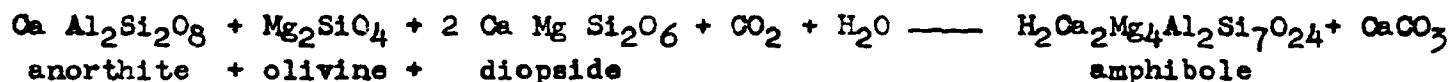
indicating an allivalitic or troctolitic bulk composition. It is probable that the rocks which were originally assemblages containing calcic feldspar, olivine or bronzite, and diopside, were transformed during metamorphism to their present state. The formation of amphibole may be attributed to the olivine or bronzite and diopside absorbing lime from the calcic feldspar which may have been An_{80} , the small amount of alkalies also entering the amphibole molecule. Chemical analyses have indicated the amphiboles to have a general composition $H_2Ca_2Mg_4Al_2Si_7O_{24}$, with a

Optical properties of hornblendes from Sittampundi rocks



REPRODUCED FROM THE ORIGINAL BY THE
 10 x 10 inch. film
 and 10 x 10

small amount of alkalies. The following reactions indicate the trends of chemical transformations resulting in the formation of amphiboles:



CHROMITE

The only metallic mineral of significance in the complex is chromite occurring in varying quantities in the chromitites which form steeply dipping layers in the anorthosite horizon, parallel to the general layering of the complex. The ore bodies run for over twenty miles along this general horizon in the complex.

Mineralogy: The chromitites are composed of clin amphibole, ortho amphibole and varying proportions of chromite, with rutile and corundum as rarer constituents. While the chromitites are essentially made up of amphiboles and chromite, the rocks of the chromitite horizon of the complex are mostly anorthite hornblende gneisses. This is an exceptional feature as in other investigated stratiform complexes the mineralogy of the chromitites is very similar to that of the entire ore horizon, except for the high proportion of ore. This peculiarity must be attributed to the metamorphic transformations undergone by these rocks, resulting in two distinct assemblages.

Chromite occurs as granular aggregates in the rock in close association with the amphiboles. While the larger grains lack any crystal form, the smaller grains show a poikiloblastic relationship with the amphiboles, and have subhedral to euhedral outlines. On the whole the chromitites may be stated to have a pseudo-porphyrritic poikilitic texture, the chromite grains being distributed on a groundmass of clino, and ortho-amphiboles. The mineral is black in color and opaque, though in thin sections the translucent edges have a pale coffee brown color. Fisher (1929) states that such pale colored varieties have generally a low chromic oxide content, which is true in the present instance. The grain size varies from 0.2 mm. to 2.0 mm., but occasionally grains up to 4 mm. are noticed.

Polished sections show subhedral and anhedral crystals of rutile, in the chromitites, both in and outside the chromite grains. The mineral is recognized by its extreme birefringence in thin sections and marked internal reflection, and white color in polished sections. The only other instance of chromite containing inclusions of rutile has been recently recorded from Turkey by Wijkersloth (1947). Professor Sampson*, on the basis of a number of new chemical analyses of pure chromite concentrates from different localities, believes that TiO_2 is invariably present in the chromite structure and that in the older analyses of chromite, TiO_2 has gone undetermined. In the fifty-two new analyses of chromite, presented by Stevens (1944), TiO_2 is invariably present varying from 0.06 to 3.00 per cent.

* Oral communication.

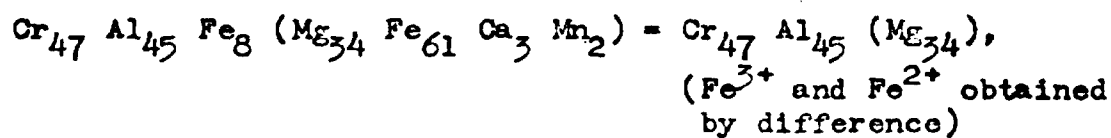
Table XXVI

COMPOSITION OF CHROMITE FROM CHROMITITE C.101

Analyst: W.H.Herdsmen

	Weight percent	Molecular ratio	3+	2+
Cr_2O_3	36.88	485	485	
Al_2O_3	24.12	473	473	
FeO	29.40	409	86	319
MgO	7.22	179		179
MnO	0.68	10		10
CaO	0.77	14		14
TiO_2	0.36	4		
SiO_2	0.34	6		
	99.77		1044	522

Formula according to Thayer's method:



NORM

Chromite (Mg,Fe) Cr_2O_4	=	46.45
Spinel (Mg,Fe) Al_2O_4	=	45.31
Magnetite $\text{Fe Fe}_2 \text{O}_4$	=	8.24
		<u>100.00</u>

Table XXVII

CALCULATION OF ATOMS PER UNIT CELL OF CHROMITE C.101
ASSUMING 8 BIVALENT AND 16 TRIVALENT METAL IONS

	%	Molecular ratios	atoms per unit cell	
Cr ₂ O ₃	36.88	.2425	Cr	7.42
Al ₂ O ₃	24.12	.2365	Al	7.24
Fe ₂ O ₃	6.80	.0430	Fe ³⁺	1.32
		.5220		15.98
FeO	23.20	.3230 - .0040 = .3190 ^a	Fe ²⁺	5.01
MgO	7.22	.1790 - .0120 = .1670 ^b	Mg	2.62
MnO	0.68	.0100	Mn	0.16
CaO	0.77	.0140	Ca	0.22
		.5260 - .0160 = .5100		8.01
TiO ₂	0.36	.0040		
SiO ₂		.0060		
RO/R ₂ O ₃ $\frac{.5100}{.5220} = 0.996$				

a = ilmenite

b = olivine

The above analysis when plotted in Triangular diagram of Stevens (1944) p.31, fig.5, falls at the boundary between the Aluminian chromite and chromian spinel.

		End Member Formula per unit cell after Stevens		
End member		Formulas/ unit cell	Formulas x M.W/ unit cell	Wt. %
Spinel	$= \frac{Al}{2}$	3.62	297	28.03
Magnesiochromite	$= Mg - \frac{Al}{2}$	-	-	-
Ferrochromite	$= \frac{Cr + Al}{2} - Mg$	4.71	584	71.73
Magnetite	$= Fe^{++} + Mg - \frac{Cr + Al}{2} - \frac{Fe^{+++}}{2}$	0.30	30	0.24

Table XXVIII

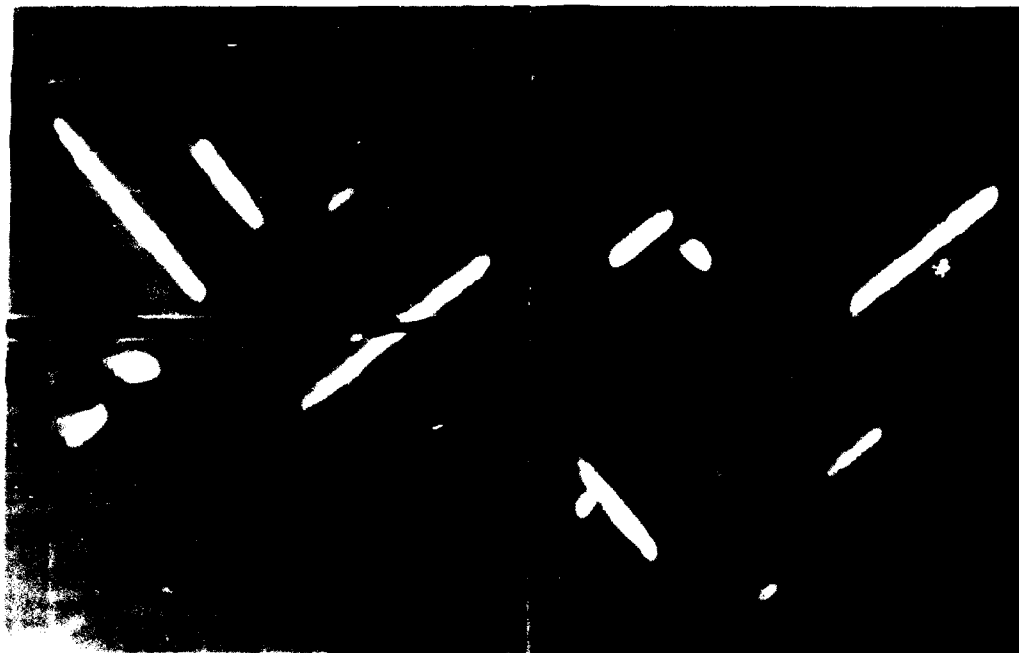
CHEMICAL COMPOSITION OF SOME CHROMITES FROM STRATIFORM SHEETS

	1	2	3	4	5	6	7	8
Cr ₂ O ₃	36.88	46.09	42.76	38.91	38.51	32.46	37.66	43.50
Al ₂ O ₃	24.12	23.81	23.85	25.29	24.57	22.70	27.30	17.23
FeO	29.40	24.05	21.51	21.93	22.17	24.16	19.01	20.86
							Fe ³⁺ 8.16	
MgO	7.22	5.43	10.36	10.77	10.06	11.33	8.66	8.70
CaO	0.77	-	-	-	-	-	-	0.10
MnO	0.68	-	-	-	-	-	-	0.23
NiO	-	-	-	-	-	-	-	0.02
TiO ₂	0.36	-	-	-	-	-	-	0.39
SiO ₂	0.34	1.02	1.68	3.50	3.68	6.00	1.66	0.30
H ₂ O	-	-	-	-	-	-	-	0.09
	99.77	100.40	100.16	100.40	98.99	99.55	100.88	100.39

1. Chromite C.101 from Chromitite band within anorthosite, Sittampundi Complex, Madras, India
2. Chromite from Benbow property, Stillwater Complex, Montana, quoted from Peoples and Howland (1940), p. 389
3. Chromite from lower group, eastern belt, Bushveld Igneous Complex, S. Africa, quoted from Kupferburger and Lombard (1937) p.25
4. to 7. Chromites from middle and upper groups of Bushveld Igneous Complex, S. Africa, quoted from Kupferburger and Lombard (1927) p.27
8. Chromite from Bird River sill complex, Manitoba, Canada, quoted from Bateman (1945) p.598



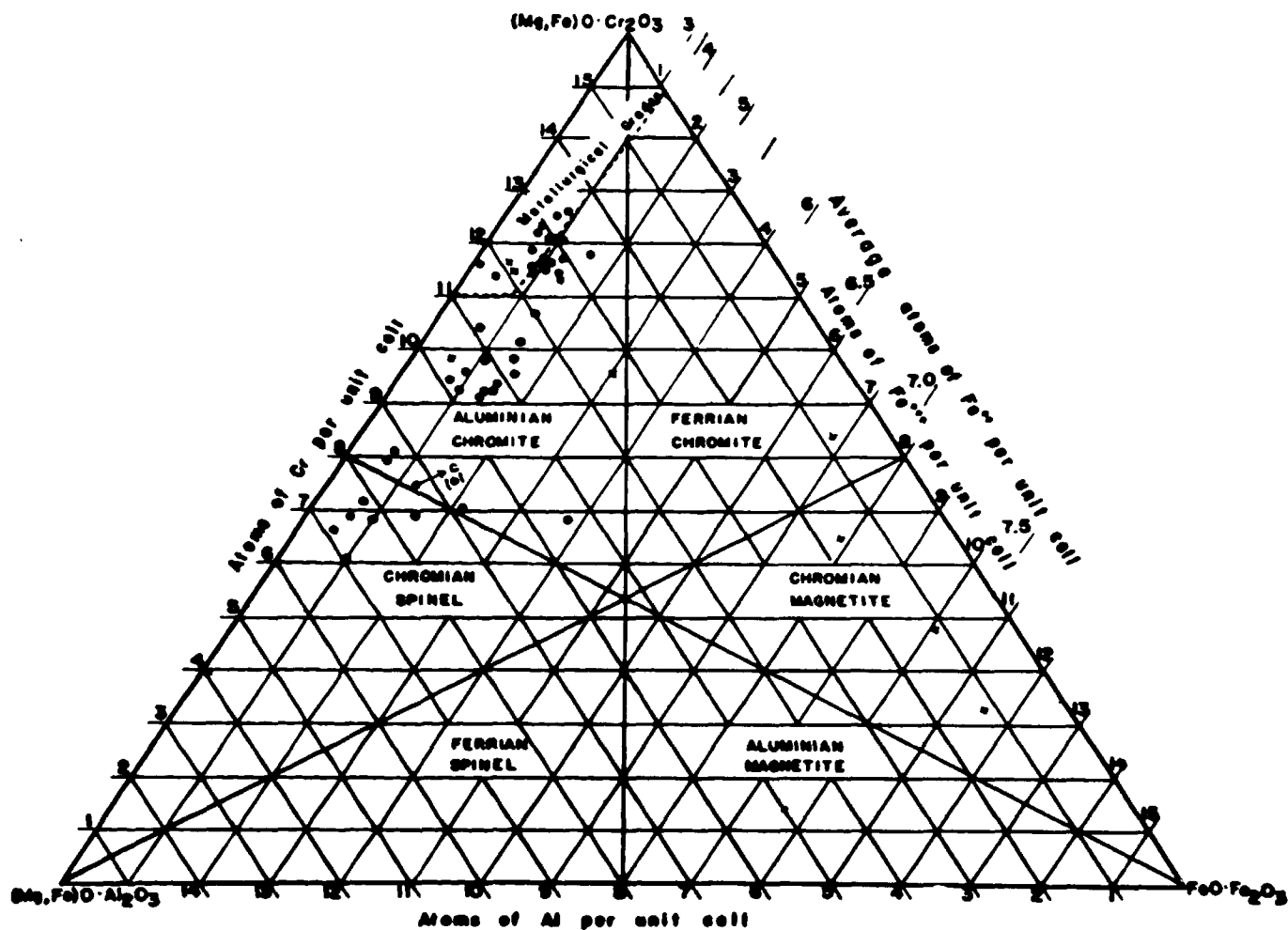
Polished section of chromitite, showing large grains of rutile in chromite. X.180



Polished section of chromitite, showing plates of unknown mineral under very high magnification. Note their geometric orientation. X. 400.

The rutile present in our chromite may represent the original TiO_2 in the chromite structure expelled during metamorphism, and subsequently crystallizing out. This explanation must be accepted with reservations until more data are available on the chemical composition of chromites which have suffered intense metamorphism. It is estimated that about two to three per cent of rutile is present in the chromitites, indicating the original chromite to be exceptionally rich in titanium. It may be pointed out that high titania chromites are known to occur at Casper Mountain, Wyoming, containing up to 3% TiO_2 .

Some grains of chromite, under high magnification, reveal the presence of fine plates of an anisotropic mineral. The mineral is white in color with marked anisotrophism and internal reflection. Its hardness is about the same as chromite and it is negative to etching reagents. These plates show a micaceous habit and their internal reflection is unlike that of rutile present in the section. The identity of this mineral is uncertain, but its disposition within the chromite is thought to be due to exsolution, consequent on unmixing, during the cooling of the chromite. Ramdhor (1931) has noticed such plates in the accessory chromites of the Bushveld norite, and identified them as haematite. In a later paper (1940) he has described such plates from the Bushveld norite as ilmenite. Brownell (1943) has also recorded such inclusions in chromite from the Bird river sill of Manitoba, identifying them as haematite. In the present instance the mineral plates do not appear to be ilmenite or haematite, judging from their optical properties, but they may represent plates of rutile with a different orientation.



Triangular diagram showing compositions of chromites and related minerals of the spinel group.

° FeO calculated.

× $RO/R_2O_3 < 1$

• $RO/R_2O_3 = 1$

The chemical analysis of this chromite is tabulated on Tables XXVI and XXVII, with calculations of the various spinel molecules after the methods of Thayer (1946) and Stevens (1944). A few comparable analyses of chromites from stratiform complexes are presented in Table XXVIII.

The composition of the chromite indicates it to be related to chromohercynite of Fisher (1929) and the ionic ratios when plotted on the triangular diagram of Stevens (1944) fall at the boundary between aluminian chromite and chromian spinel. The molecular formula calculated from the analysis indicates nearly forty-five per cent of spinel molecule, proving the impossibility of beneficiating the ore to a higher grade by mechanical means.

PYROXENES

Clinopyroxene: Pyroxene is rare in the rocks of this complex, which may be attributed to its transformation to amphibole during metamorphism. In the anorthositic rocks a few thin sections showed skeletal crystals of clino-pyroxene altering to amphibole. Under high power the mineral has a pale green color with a fairly distinct cleavage, and the following optical properties:

C.53 $2V = + 59 \pm 1^\circ$, C Z $43 \pm 1^\circ$

C.128 $2V = + 60 \pm 1^\circ$, C Z $42 \pm 1^\circ$

The above optical properties indicate them to belong to the diopside-hedenbergite series according to the recent curves of Hess (1949).

The eclogites and websterites contain clinopyroxenes with the following optical properties:

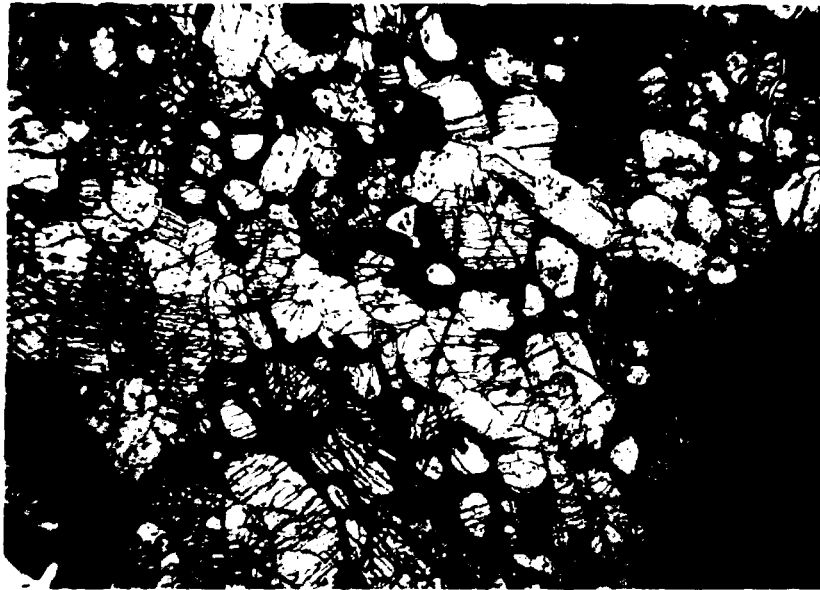
<u>No</u>	<u>N_x</u>	<u>N_z</u>	<u>2V</u>	<u>C ^ Z</u>	<u>Rock</u>
C.19	-	-	+ 57 ± 1	38 ± 1	Bronzitic pyropite
C.20	1.681 ± 002	1.709 ± 002	+ 56 ± 1	42 ± 1	Websterite pegmatite
C.41	1.681 ± 002	1.708 ± 002	+ 58 ± 1	43 ± 1	Eclogite
C.43	1.670 ± 002	1.699 ± 002	+ 60 ± 1	-	Websterite
C.60	1.680 ± 002	1.709 ± 002	+ 59 ± 1	44 ± 1	Bronzitic pyropite
C.122	-	-	+ 58 ± 1	-	Eclogite

The above properties indicate them to be in the diopside-salite range in the diopside-hedenbergite series.

The above monoclinic pyroxenes have diallagic structure due to the well-developed 100 parting. Uralitization of these clinopyroxenes has given rise to an abundance of green amphibole.

Orthopyroxene: The eclogites and websterites carry a fair proportion of orthorhombic pyroxene and the optical properties of some of them are as below:

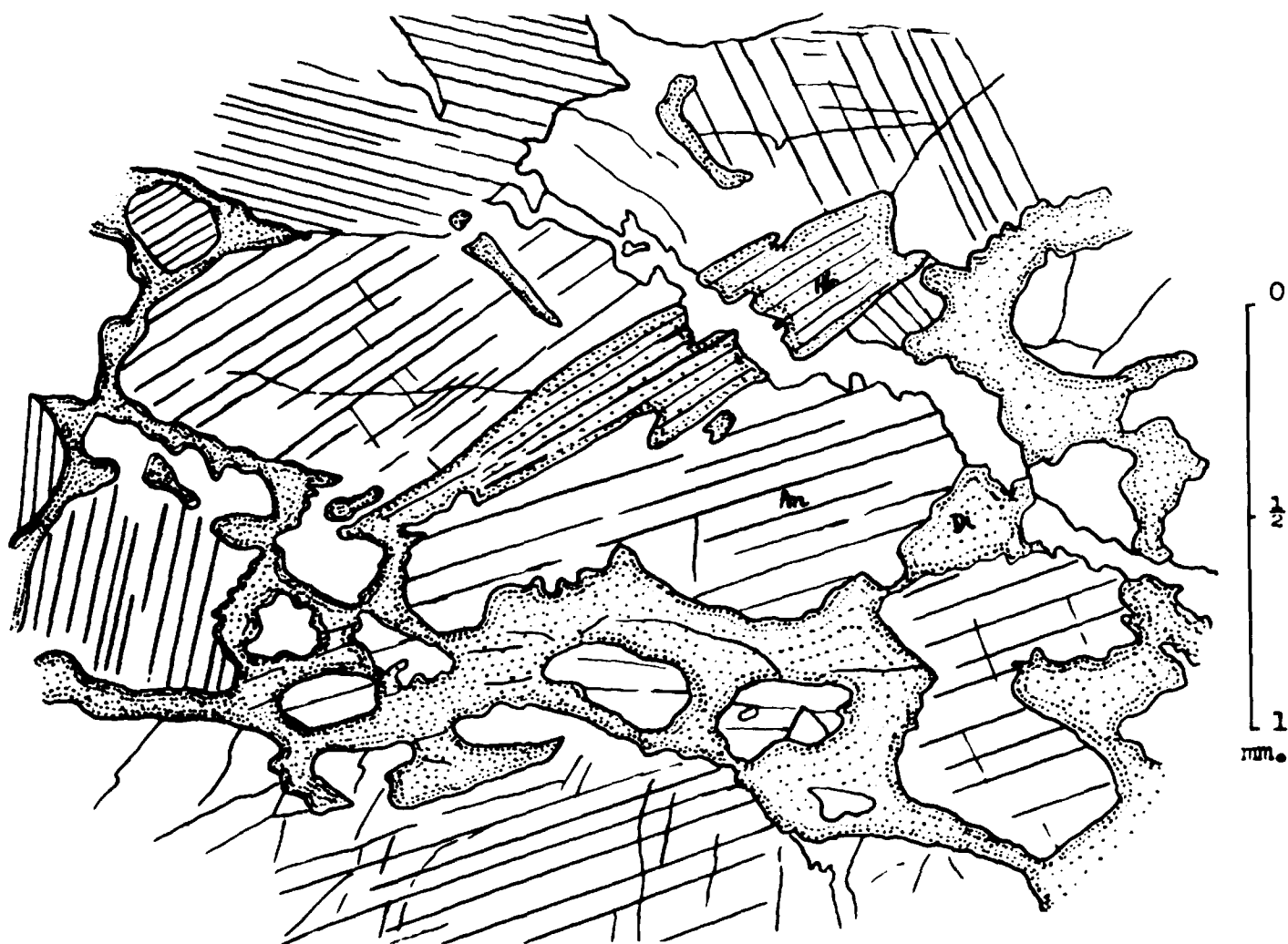
<u>No.</u>	<u>N_z</u>	<u>%Enstatite</u>	<u>Rock</u>
C.19	1.685 ± 002	84	Bronzitic pyropite
C.20	1.689 ± 002	78.5	Websterite pegmatite
C.36	1.682 ± 002	86	Eclogite
C.41	1.683 ± 002	84.5	Eclogite
C.43	1.695 ± 002	77.0	Websterite
C.60	1.685 ± 002	84	Bronzitic pyropite
C.122	1.684 ± 002	85	Eclogite



Skeletal crystals of diopside in anorthosite. X 22



Ilmenite, rutile and sphene in anorthosite. X.7



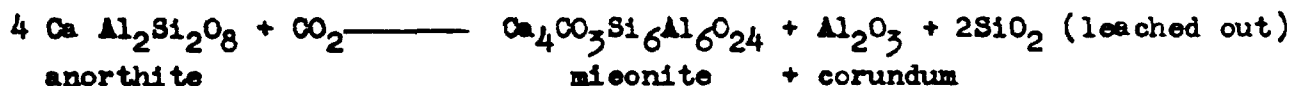
Skeletal crystals of diopside in anorthite gneiss . Note
their alteration to hornblende

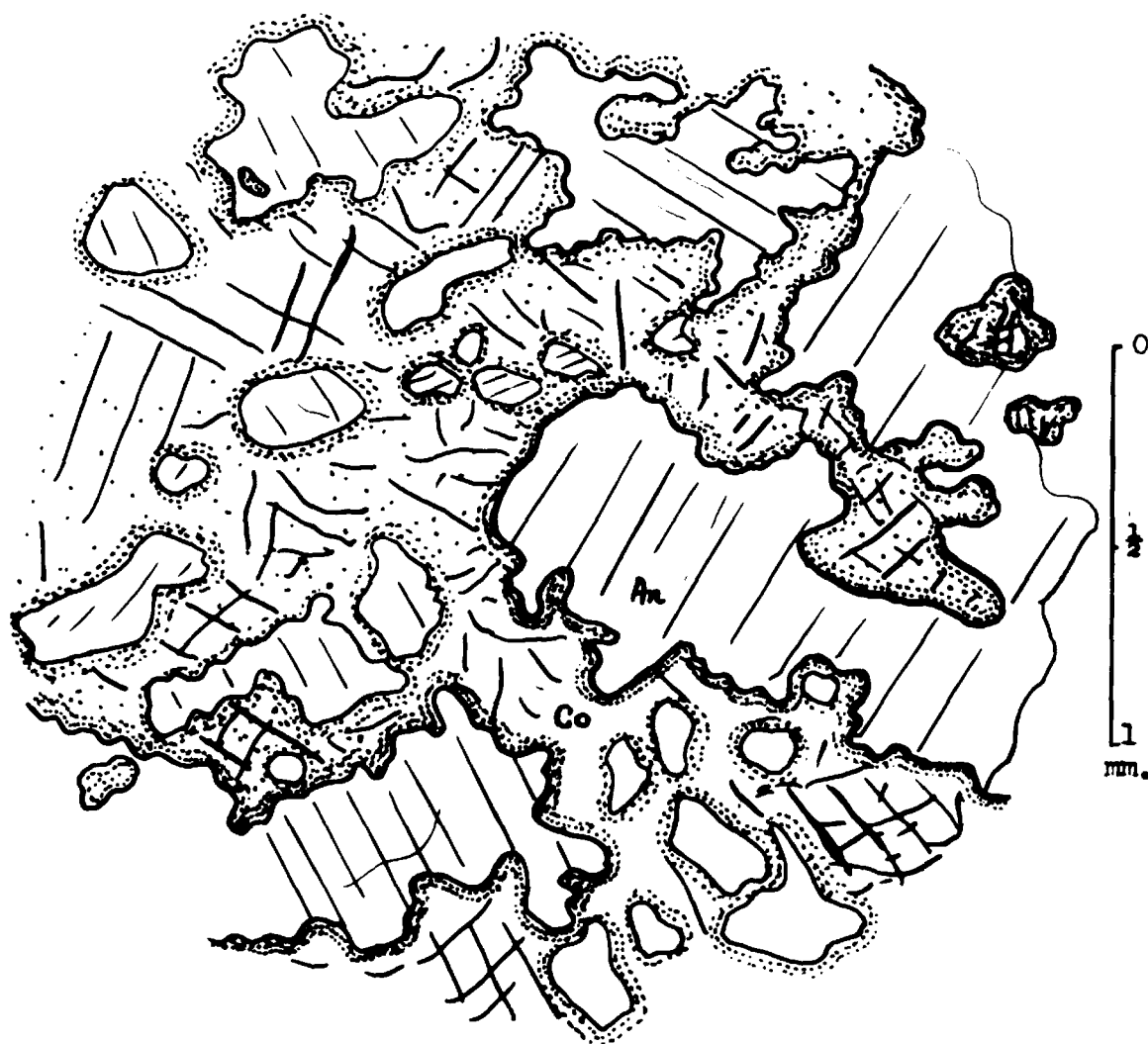
The above characters conform to those of bronzite and hypersthene, and the enstatite percentages shown are from the curve of Hesse and Phillips (1940). These orthopyroxenes have well-developed lamellae, characteristic of slow-cooled rocks like many gabbros in ultramafic complexes. It may be noted that the orthopyroxene is bronzite in the eclogites and hypersthene in the websterites.

Scapolite: Many of the anorthositic rocks contain scapolite, invariably as an alteration product of the calcic plagioclase. The mineral is readily distinguished from the accompanying plagioclase by its lower refringence and much higher birefringence. Fragments of the mineral were removed from thin sections for index determination and the values are recorded below, together with the anorthite content of the related plagioclase:

	<u>N_E</u>	<u>N_O</u>	<u>% of Meionite (after Winchell)</u>	<u>% An in plagioclase</u>
0.50	1.552	1.582	70	98
0.71	1.548	1.576	65	91
0.82	1.548	1.576	65	86

As may be seen above, the meionite content of the scapolite varies with the anorthite content of the plagioclase from which it is derived. This observation is contrary to that of Turner (1948), who states that scapolites derived from plagioclases An₄₅, An₈₀, and An₉₅ had almost constant composition. The following reaction shows the trend of transformation of anorthite to scapolite:





Corundum replacing anorthite in anorthite corundum rock.

Corundum: Corundum is sparsely distributed in the anorthositic rocks and interbanded chromitites. The mineral occurs as euhedral and subhedral prismatic crystals, varying in length from a fraction of a centimeter to nearly fifteen centimeters. Well developed crystals showing combinations of hexagonal prism, base and rhombohedron, are occasionally found in the anorthositic rocks. Corundum in the chromitites has a pleasing ruby red color, while in the anorthosites they range from greyish white to pale green, and the color of the former may be attributed to traces of chromium. Occasionally the corundum crystals, which form porphyroblasts in the anorthosites, have a thin shell of calcite.

Under the microscope corundum is easily distinguished by its high relief and low birefringence, and occasionally is seen replacing anorthite. The pink corundum found in the chromitites is pleochroic in thick sections in shades of ruby. The densities of the two types of corundum determined on small fragments are given below:

1. White corundum from anorthite gneiss 3.943 gm/cm^3 at 26.0°C
2. Pink corundum from chromitite 3.913 gm/cm^3 at 26.0°C

Sillimanite: Sillimanite occurs as acicular crystals and aggregates in cordierite and calcic plagioclase, in a cordierite-corundum-anthophyllite-anorthite assemblage. The identity of the mineral is established by its low optic axial angle, form, and general occurrence in cordierites.

Rutile: In several thin sections of chromitites, a mineral with extreme birefringence and very high relief was noticed. Optically it was found to be uniaxial and positive. Polished sections of some of the above chromitites showed the mineral in abundance, having a brilliant white

color and marked internal reflection. These properties indicate the mineral to be rutile. A sample of crushed chromitite when passed through the electromagnet at a very high field strength yielded a small amount of non-magnetic concentrate composed of prismatic crystals with a brilliant red color and adamantine luster, the identity of which was confirmed to be rutile by x-ray examination. It is thought that the mineral represents titania released from the chromite structure during metamorphism.

Sphene: This is a rare constituent in the rocks of the complex. In one specimen of anorthositic rock a fair aggregate of sphene was found developed round a central core of rutile (photomicrograph). The mineral was recognized by its high relief, strong birefringence, and strong dispersion, and biaxial positive nature. It is likely that the mineral has developed by reaction between calcic plagioclase and ilmenite during metamorphism.

Secondary chlorite and talc are found in some of the chromitites developed at the expense of the ortho, and clino-amphiboles. Spinel, calcite, apatite, and ores (magnetite and ilmenite) are rare accessory minerals in the rocks of the complex.

SUMMARY

The mineralogy of the complex as a whole shows it to be rich in the 'hydroxyl' molecule, as indicated by the abundance of amphiboles and minerals of the epidote-clinozoisite series. The extremely calcic nature of the plagioclase must be attributed to the removal of soda, and the formation of epidote-clinozoisite and corundum is indicative of the role of water and other mineralizers in the evolution of rocks with a 'hydroxyl' rich paragenesis. This is in conformity with the experimental results

of Yoder (1951), who states that the presence of an "excess" or "deficiency" of water vapor greatly influences the mineralogy of a metamorphic rock.

CHAPTER IV

PETROGRAPHY

The rocks of this complex can be divided into two main series, on the basis of their petrographic characters and mineral assemblages. The anorthosite series consist of a group of felsic rocks containing a very high proportion of calcic plagioclase, and a variable amount of edenite, clinozoisite, garnet, and corundum. Johannsen (1937) has defined anorthosites as rocks which are practically free from dark minerals, and anorthitites, as calcic plagioclase equivalent of anorthosite. However, the term anorthosite has been extended to rocks containing up to 10% mafic minerals, by Buddington (1939), and some of the more mafic varieties are described as noritic anorthosite and gabbroic anorthosite. The anorthositic rocks of the Sittampundi complex have a variable proportion of mafic minerals, and are thought to represent what were originally different facies of true anorthosites. The term anorthosite series has, therefore, been adopted to designate a group of gneissic rocks essentially made up of calcic plagioclase, of composition An_{80-100} , with minor amounts of edenite (hornblende), epidote-clinozoisite, garnet (grossularitic) and corundum. The eclogite gabbro series consists of a group of garnet pyroxenites and amphibolites, varying from biminerally to polymineralic assemblages. The general term eclogite gabbro series has been adopted to describe these rocks. Besides these two main types, there are several bands of chromitites and perknites within the anorthosite belt, as well as small bodies of websterite (pyroxenite) within the limits of the complex.

ANORTHOSITE SERIES

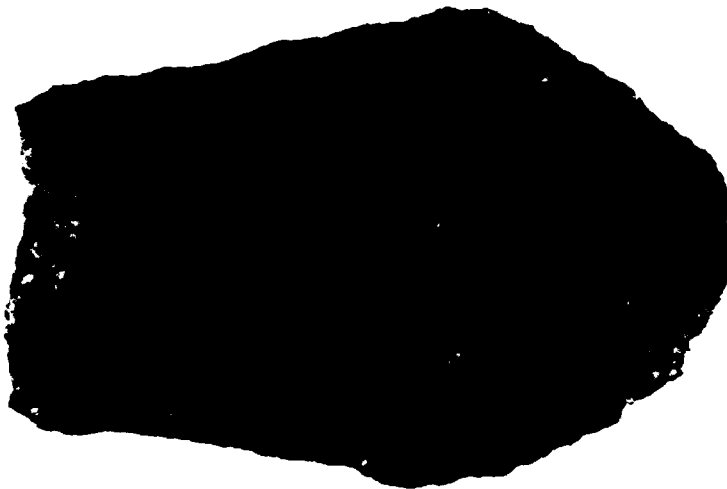
A major portion of the complex is made up of rocks of the anorthosite series, and some of the typical assemblages noticed are:

APPROXIMATE MODES OF ROCKS FROM THE SITTAMPUNDI COMPLEX

Minerals	1	2*	3	4	5*	6	7	8*	9	10*	11	12	13	14	15	16	17	18	19	20
Quartz	+	+	+	+	+	+	+	+	+	+	+	+	+	+	1.5	+	+	+	+	+
Plagioclase	93.0	89.2	87.1	81.0	79.1	78.2	74.3	69.7	68.0	66.1	65.6	12.6	20.2	22.4	19.3	17.5	7.5	1.4	+	+
Clino-amphibole	0.5	5.3	10.3	7.0	20.9	1.3	23.2	21.8	18.4	+	0.2	85.0	+	21.3	12.8	16.3	24.3	2.2	22.2	27.0
Ortho-amphibole	+	+	+	+	+	+	+	8.2	9.7	+	+	+	4.0	+	+	+	+	+	10.0	8.8
Clinopyroxene	1.8	2.4	+	2.8	+	+	0.5	+	+	+	+	+	+	4.4	7.0	7.1	14.1	5.3	+	+
Orthopyroxene	+	+	+	+	+	+	+	+	+	+	+	+	+	3.9	7.2	6.4	8.3	7.2	+	+
Clinzoisite	3.7	3.1	2.2	4.8	+	8.7	+	+	+	21.1	20.4	2.0	1.4	+	+	+	+	+	+	+
Corundum	+	+	0.4	1.4	+	5.3	1.4	+	+	+	6.0	+	21.2	+	+	+	+	+	+	1.0
Garnet	+	+	+	+	+	4.4	+	+	+	7.2	3.8	+	+	31.2	32.3	39.8	29.4	72.4	+	+
Scaevolite	0.7	+	+	2.0	+	1.3	0.6	+	2.4	4.2	3.2	1.7	4.4	1.7	+	+	+	+	+	+
Sillimanite	+	+	+	+	+	+	+	+	+	+	+	+	5.0	+	+	+	+	+	+	+
Cordierite	+	+	+	+	+	+	+	+	+	+	+	+	30.8	+	+	+	+	+	+	+
Calcite	+	+	+	0.4	+	0.3	+	+	1.0	1.4	0.8	0.7	2.0	+	+	+	+	+	+	+
Chromite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	54.3	59.2
Ores	0.3	+	+	0.6	+	+	+	+	0.5	+	+	+	0.5	1.2	1.5	1.1	2.3	1.2	+	+
Spinel	+	+	+	+	+	+	+	0.3	+	+	+	+	0.5	0.7	+	0.4	+	+	+	+
Rutile	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	2.5	0.5
Talc	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	0.5	3.5
Kelyphite	+	+	+	+	+	+	+	+	+	+	+	+	+	9.2	19.2	10.9	14.1	9.8	+	+

* Analyzed specimens, G.100, G.77, G.69, G.50, G.71, G.41.
 All modes are expressed as percent percentages.
 1 to 11 Anorthositic rocks.
 12 Mafic band in anorthosite.

13 Cordierite-corundum-anthophyllite rock.
 14 to 18 Eclogite gabbros. (18 is bronzitic pyroxite)
 19 and 20 Chromitites.



Hand specimens of anorthosite with porphyroblasts of corundum. Note the hornblende crystals wrapping around the corundum, and the pressure shadows on either side of the corundum crystals.

- i) Bytownite-anorthite edenite gneiss
- ii) Anorthite corundum edenite gneiss
- iii) Anorthite clinozoisite garnet rock
- iv) Anorthite garnet clinozoisite corundum gneiss
- v) Bytownite clinozoisite edenite gneiss
- vi) Schistose edenite gneiss
- vii) Anorthite anthophyllite edenite rock

In the field the anorthosite series is characterized by a perfect alternation of felsic and mafic bands and by the persistence of concordant seams of chromitite over several miles along the strike. The felsic bands are rich in clinozoisite, corundum, and garnet, while the mafic bands contain variable proportions of edenite. The leucocratic rocks simulate marbles in appearance in that they have a saccharoidal texture and a megascopic resemblance of the minerals present to typical mineral assemblages of marbles. The more mafic types are even-grained, with pronounced gneissic texture accentuated by the preferred orientation of the edenite crystals in the plane of foliation. It may not be incorrect to call some of these rocks amphibolites, and Hadley (1949) has adopted the name edenite amphibolite for certain bytownite edenite gneisses of Carolina.

Hand specimens of anorthositic rocks are pale grey to white in color, depending on the percentage of mafic minerals present, with occasional porphyroblasts of corundum. The strong lineation and planar structure are discernible in fair sized hand specimens. The density of these rocks varies from 2.75 to 2.93 gm/cm³.

These rocks contain the following minerals in order of abundance:

- 1) Calcic plagioclase An₈₀₋₁₀₀, ii) edenite, iii) epidote clinozoisite,
- iv) anthophyllite, v) diopside, vi) corundum, vii) garnet, viii) scapolite
- ix) calcite, x) sphene, xi) rutile and xii) apatite, the last 3 being relatively

rare. The optical properties and chemical composition of some of these minerals have been discussed in Chapter III. The modal composition of some of these rocks are presented in Table XXIX.

In thin section these rocks display a more or less equigranular interlocking texture with the plagioclase forming a mosaic of polygonal crystals, in which the other minerals are distributed, some with a preferred orientation. The plagioclases display a dimensional orientation which is apparent when the gypsum plate is introduced with the nicols crossed. Sohnge (1945) has noticed a similar preferred orientation of feldspar grains parallel to the banded structure in the anorthosite gneisses of Messina. He attributes this to the recrystallization of the rocks, according to Riecke's principle whereby crystals become elongate in the direction of least pressure, as solution takes place more readily at the points of greater stress. Planar structure is not generally perceptible in thin sections, though gneissic structure is marked in some of the mafic anorthosites. Edenite and in some rocks anthophyllite occur as acicular and bladed crystals with a preferred orientation, their longer axis being in the plane of layering. These prismatic crystals display a parallelism to one another. The epidote clinozoisite group of minerals present in these rocks also display a preferred orientation and show euhedral to subhedral forms. Occasionally skeletal crystals of diopside are encountered undergoing paramorphic alteration to edenite. Garnet is rather restricted in occurrence and when present is seen replacing anorthite. Corundum occurs as porphyroblasts in the rocks generally with a thin rim of calcite. Most of the other minerals occur in very minor amounts. A brief

description of the mineralogy of the rocks follows.

Plagioclase

The plagioclase feldspar in these rocks varies in composition from An_{80} to An_{100} , and in their longest dimension measure from 0.3mm to 4 mm. They are exceptionally fresh due to recrystallization, and are devoid of alterations normally noticeable in calcic feldspars. Occasionally calcite and scapolite are seen to derive from the feldspar. Untwinned crystals make up a fair proportion of the feldspar and the twinning noticeable in the others is generally of the simple type, with a fair proportion of complex twins.

Edenite

The monoclinic amphibole present in the anorthositic rocks has been identified as edenite on the basis of its chemical composition and optical characters. The optical properties are : $N_x = 1.649 - 1.658$, $N_y = 1.658 - 1.669$, $N_z = 1.667 - 1.680$; $Z_{Ac} = 18 \pm 2^\circ$; $2V = -79 - 85^\circ$; $r < v$; $X < Y < Z$; pleochroic in yellowish and bluish greens. The mineral occurs as prismatic crystals measuring from 0.2 mm. to 2 mm. and occasionally 4-5 mm.

Anthophyllite

This mineral is encountered in some of the more mafic anorthosites, and occurs as long bladed crystals in a matrix of calcic feldspar. The optical properties and chemical composition establish its identity with gedrite or according to Rabbitt aluminian anthophyllite. The optical properties of the mineral are : $N_x = 1.642$, $N_y = 1.649$, $N_z = 1.658$; $2V = +88^\circ$; $Z = c$, $X = Y < Z$, pale tan grey to clove brown.

Epidote-clinozoisite

This group of minerals occurs in fair abundance in these rocks, and judging from the optical properties contains 5 to 25% epidote molecule. They are characterized by intense zoning which is attributable to compositional variation within a single crystal. The optical properties measured are: $N_x = 1.715 - 1.720$, $N_y = 1.716 - 1.730$, $N_z = 1.719 - 1.733$; $r < v$ to $r > v$; $2V_x = 85^\circ$ to 95° ; $X \wedge c = 0 - 36^\circ$. The minerals occur as anhedral, subhedral and euhedral crystals, and the grains measure along their longest dimension from 0.2 mm. to 4 mm. Very often they exhibit a replacement relationship with the calcic feldspar.

Garnet

Occasionally pale brownish pink garnets are associated with the leucocratic varieties in close association with clinozoisite and corundum. Chemical analysis indicates it to be a variety rich in the grossularite molecule with a fair proportion of almandite and pyrope molecules. Invariably it is seen replacing anorthite and occasionally paramorphic change from garnet to clinozoisite and garnet to vesuvianite (?) are discernible. The mineral occurs as rounded grains measuring from 0.1 mm. to 4 mm. in diameter. One unique specimen of rock shows almost complete replacement of anorthite by this garnet.

Clinopyroxene

In a few thin sections of mafic anorthosite, skeletal crystals simulating 'atolls' are seen undergoing alteration to edenite. Optical properties measured on several grains are: $2V = +59-60^\circ$, $Z \wedge \phi = 42^\circ - 44^\circ$,

indicating their affinities with the diopside-hedenbergite series. Index determinations could not be accomplished due to difficulties in separation of such minute grains. These grains have widths from 0.1 mm. to 0.5 mm. and vary in length from 0.5 mm. to 2mm.

Corundum

Porphyroblasts of corundum are scattered in the anorthositic rocks. They occur as subhedral and euhedral crystals, and as tiny basal plates, generally accompanied by a thin rim or shell of calcite. These crystals vary in diameter from 0.2 mm. to 50 mm., and occasionally larger crystals are seen. They are readily distinguished in thin section by the high index of refraction and uniaxial character. Occasionally corundum displays a replacement relationship with anorthite and sometimes shows alteration to a micaceous mineral.

Scapolite

Scapolite derived from the calcic feldspar is noticed in several rocks, and there appears to be specific relationship between the composition of the mineral and the feldspars from which it is derived, and this has been discussed earlier. The mineral is recognized by its low indices of refraction, $N_g = 1.548-1.552$, $N_o = 1.576-1.582$, and high birefringence as compared with the associated plagioclase. The composition deduced from the indices of refraction indicates 65 to 70% meionite molecule, according to Winchell (1951).

Calcite

Occurs as granular aggregates resulting from alteration of anorthite, and as a thin granular rim around some of the corundum crystals.

Sphene

Pale yellow crystals of sphene were noticed only in one rock forming an eugen shaped aggregate around a central core of rutile and sphene. So far it has not been recognized in more than five, of over 200 thin sections of anorthosites.

Rutile and apatite

Extremely rare and noticed in one or two thin sections.

Petrographic descriptions of some of the principal varieties of anorthositic rocks follow:

Anorthite edenite (hornblende) gneiss. C.33

Hand specimens show typical gneissic structure, due to the platy parallelism of the plagioclase crystals and the dimensional orientation of edenite prisms. In appearance it simulates a feldspathic amphibolite, and has dark grey color. The density of this type is 2.825 gm/cm^3 . Thin sections indicate this type to be essentially bimineralic with a trace of ores in some slices. The measured modal composition in weight per cent is:

Anorthite (an ₉₀₋₉₆)	79.1
Edenite	20.9

The texture is granulitic, composed of a mosaic of polygonal plagioclase crystals in which dimensionally oriented idiomorphs of edenite prisms are scattered. Preferred orientation of the plagioclase is brought out under crossed nicols.

The plagioclase is anorthite with An₉₀₋₉₆, and displays an equal proportion of twinned and untwinned crystals. A few crystals display complex twin laws. Edenite as pale green prismatic crystals with the following optical properties: $N_x = 1.652$, $N_y = 1.661$, $N_z = 1.669$;

$2V = -84 \pm 1^\circ$; $2 \wedge c = 17 \pm 1^\circ$; $r < v$; $X < Y < Z$ in yellowish to bluish green. The plagioclase grains measure from 0.6 mm. to 1 mm. in length and the edenite prisms from 1 to 3 mm. Occasionally this type carries prophyroblasts of corundum. A representative specimen of this type has been chemically analyzed.

Anorthite-clinozoisite-garnet rock: C.50

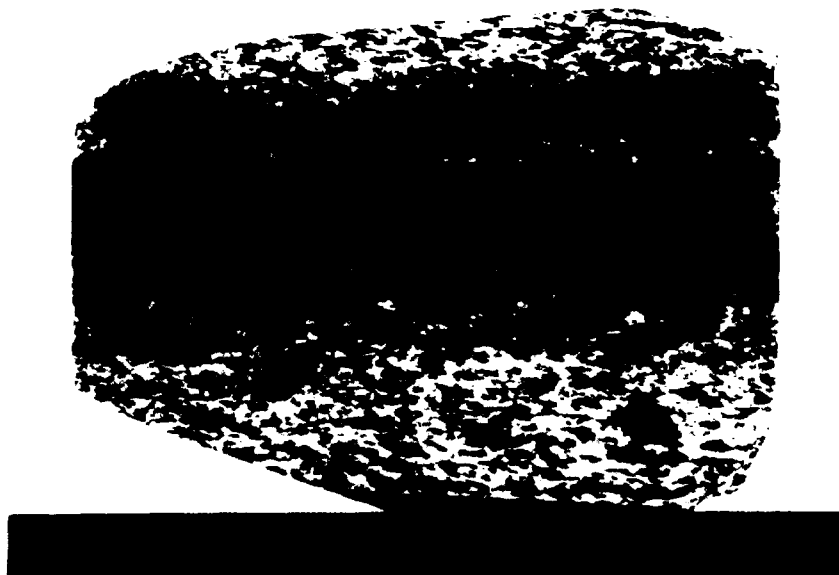
This type is conspicuous by the total absence of amphibole, and the abundance of clinozoisite. Hand specimens closely resemble a marble, in texture and general appearance. The density of this type is 2.934 gm/cm^3 . Thin sections display a coarse crystalloblastic texture, and the grain size of the various minerals measured along their longest dimension are : plagioclase, 0.8 mm. to 2.5 mm.; clinozoisite, 0.5 mm. to 5 mm.; garnet 0.5 mm. to 1.5 mm.; and scapolite 1 mm. to 2 mm. The modal mineralogical composition of this type in weight per cent is as below:

Anorthite(An_{98})	66.1
Clinozoisite	21.1
Garnet	7.2
Scapolite	4.2
Calcite	1.4

The plagioclase in this rock is unique in being almost pure anorthite, and is remarkably fresh. Over a dozen thin sections were examined on the five axis stage, and the plagioclase crystals found to exhibit several twin laws, including complex types. The clinozoisite present is very low in epidote molecule as indicated by the refractive indices: $N_X = 1.715$, $N_Y = 1.716$, $N_Z = 1.718$. The garnet is of the grossularite variety with $N = 1.768$. Another mineral closely resembling this garnet and clinozoisite is present in some



Coarse anorthosite with blades of anthophyllite, in a matrix of granular anorthite.



Layer of chromitite in hand specimen of anorthosite. Note knife edge contact of layer.

anorthosites of this type and is suspected to be vesuvianite. Scapolite is present secondary after the anorthite and the indices of refraction for these grains, $N_E=1.552$, and $N_O=1.582$, indicate nearly 70% melonite molecule for the mineral. Occasionally corundum is associated with this variety as porphyroblastic crystals. The clinozoisite and garnet in this rock are seen replacing anorthite and are therefore of later origin. A representative sample of this type has been analyzed.

Anorthite-anthophyllite-edenite rock -C.69

This is an unusual type with limited distribution, and interpreted as a pegmatitic phase of the anorthosite. It simulates in megascopic appearance the feather amphibolite of the Grenville terrane described by Adams and Barlow (1910). Hand specimens of this type consist of finely granular anorthite with dimensionally oriented edenite prisms with a marked lineation, and large prismatic crystals of anthophyllite which are oriented with their longer axis parallel to the plane of banding, but in all azimuths within that plane. The density of this type is 2.833 gm/cm^3 .

Thin sections of this type display a mosaic texture, composed of polygonal crystals of anorthite, with prismatic crystals of edenite and anthophyllite aligned in the matrix of anorthite. Occasionally large blades of edenite show a diablatic relationship and enclose small grains of pure anorthite (An_{98}). The grain sizes of the various minerals measured in their direction of maximum elongation are: plagioclase 0.6 to 1.5 mm; anthophyllite 3 to 14 mm., occasionally up to 10 cm.; edenite 1 to 3 mm. occasionally up to 5 cm. The approximate modal mineralogical composition in weight per cent is tabulated below:

Plagioclase An_{90-92}	69.70
Anthophyllite	8.20
Edenite	21.80
Spinel	0.30

The feldspar is anorthite An_{90-92} , and is very fresh, though displaying incipient scapolitization. Anthophyllite is obviously an aluminian variety with $N_z=1.659$, which is very nearly the same as that of an analyzed specimen of the mineral from a similar rock. The mineral is easily distinguished from the edenite by its straight extinction and characteristic absorption in shades of tan and clove brown. The edenite in this rock has the following optical characters: $N_x=1.649$, $N_y=1.659$, $N_z=1.667$; $2V = -84^\circ$; $r < v$; $X < Y < Z$ in yellowish and bluish green. The above optical properties indicate a composition very close to that of the analyzed edenite C.34. Small grains of green spinel are seen scattered in the ground mass feldspar, and may have been formed during the production of amphibole from the primary pyroxenes.

Bytownite clinozoisite edenite gneiss C.128

This type is characterized by a fine grained texture, with a smaller grain size. Clinozoisite and edenite show a dimensional orientation and the rock as a whole has a pearl grey color with a density of 2.751 gm/cm^3 . Thin sections display an inequigranular xenoblastic texture, with marked mutual interference of grains. The plagioclase feldspars vary in length from 0.1 mm. to 1.2 mm, the edenite prisms from 0.5 mm. to 1.0 mm, clinozoisite from 0.4 mm. to 7.0 mm., and the diopside skeletal crystals measure 0.2 mm. in width and 1.5 to 3.0 mm. in length. The modal composition of this type is shown below:

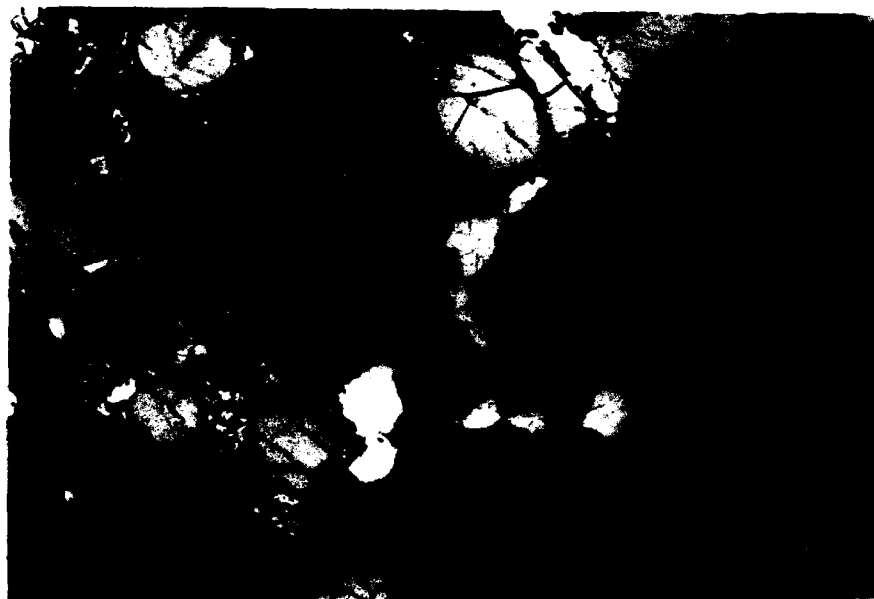
Plagioclase (An_{84-88})	89.2
Clinopyroxene	2.4
Edenite	5.3
Clinozoisite	3.1



Anorthosite displaying mosaic texture. X. 10



Anorthosite, showing preferred orientation of plagioclase and edenite. X. 7



Eclogite gabbro. Note bronzite, diopside and plagioclase around the garnets. X.9



Bytownite gneiss (anorthosite). Note the gneissic texture and abundance of untwinned plagioclase.
X. 7

The plagioclase feldspar in this type is bytownite with compositional range An_{84-88} , and forms a mosaic aggregate of polygonal grains, which are for the most part untwinned. Skeletal crystals of diopside are seen interstitially in the plagioclase mosaic undergoing paramorphic alteration to edenite. The optical properties of this clinopyroxene: $2V = + 60^\circ$, $Z \wedge c = 43^\circ$, indicate it to be in the diopside-hedenbergite group. The edenite has the following optical characters: $N_X = 1.657$, $N_Y = 1.669$, $N_Z = 1.679$; $2V = -79.5^\circ$; $Z \wedge c = 18^\circ$; $r < v$; $X < Y < Z$, yellowish to bluish green. In comparison with the analyzed edenite this appears to be an iron rich variety. The clinozoisite is intensely zoned and indicated two distinct compositions, as may be seen from the values for the indices of refraction $N_X = 1.718$ and 1.730 , $N_Z = 1.729$ and 1.766 . The higher values indicate a higher proportion of epidote molecule. This type is fairly conspicuous in the anorthosite belt, and is more resistant to weathering, as may be seen from the fact that it forms low hills. Corundum is infrequent in this type. A representative sample of this has been chemically analyzed.

Schistose edenite gneiss C.15

Within the anorthosites there are several mafic bands composed mainly of monoclinic amphibole. In hand specimen these perknites have a schistose texture due to the platy parallelism of the amphibole crystals. The rocks are dark green and have a density of 3.0 gm/cm^3 . The approximate modal composition of this type is:

Edenite	83.0
Plagioclase	12.6
Clinozoisite	2.0
Scapolite	1.7
Calcite	0.7

Thin sections display a schistose texture being essentially an aggregate of edenite crystals with interstitial plagioclase and clinozoisite. Scapolite and calcite are seen forming at the expense of the plagioclase. The edenite crystals vary in length from 0.8 to 8 mm., and have the following optical characters: $N_X=1.651$, $N_Y=1.661$, $N_Z=1.669$; $2V = -83^\circ$; $X < Y < Z$ in yellowish and bluish green.

The above general description of some of the principal types adequately summarizes the petrographic characters of the anorthosite series. Besides the types described, there are types with a variable assemblage of the minerals described, but the general textural and paragenetic relationship remain the same. The petrography of these rocks indicate a remarkable homogeneity in the composition of the minerals and the variations noticeable are quite normal. It has been found also the distribution of corundum is not dependent on the mineral composition of the rock type as porphyroblasts of corundum occur in all the types, but appears to be controlled by the composition of the plagioclase, as in the bytownite bearing rocks corundum is of exceptional occurrence.

The anorthosite series are characterized by the presence in them of seams of chromitite varying in thickness from a few inches up to over ten feet. These chromitites consist essentially of amphiboles with a variable proportion of ore. Chromitite has been defined by Johannsen (1937) as a rock composed essentially of chromite, and if any pyribole is present in quantities over 5% it should be prefixed by the same type of pyribole. In view of the fact that the chromitites under consideration consist only of about 55 to 75% chromite, the rest being made up of a monoclinic amphibole identified as pargasite; these chromitites are

strictly pargasite chromitites by definition. However, the term chromitite is adopted here to indicate such rocks. Besides the chromitites, there are hypermelanic bands made up essentially of amphiboles, associated with them.

Chromitite

In hand specimen these rocks are greenish black, the chromite displaying a metallic lustre. The amphiboles show a preferred orientation conformable to that in the anorthosites. The proportion of ore in these rocks is variable ranging from 50 to 85%, but the average would be about 60%. The chromite is distributed as granular aggregates in a groundmass of amphiboles. In thin section these chromitites show a pronounced schistose texture and the preferred orientation of the amphiboles is discernible. The rocks may be stated to have a pseudo-porphyrritic poikilitic texture, the chromite grains being distributed on a groundmass of monoclinic and orthorhombic amphiboles. The chromite grains have euhedral to subhedral form and thin edges are semitranslucent with a coffee brown color. The chromite grains have diameters varying from 0.02 mm. to 2 mm. Some of the chromite grains carry small insets of rutile. The monoclinic amphibole present has the following optical characters: $N_x = 1.640$, $N_x = 1.647$, $N_z = 1.656$; $Z \wedge c = 19^\circ$; $2V = +85.5^\circ$; $r > v$; $X = Y < Z$, pale green to emerald green. Chemical analysis of this type of amphibole indicates it to have affinities with pargasite. The orthorhombic amphibole present in these chromitites has an unusual play of colours apparently caused by the presence of chromite inclusions. The refractive index N_z for the orthorhombic amphibole is 1.637 and 1.643 for different specimens. The low values for the index indicates a more magnesian composition as compared with the anthophyllites

in the anorthosites. Green spinel, corundum and talc are present in minor amounts.

Cordierite-corundum anthophyllite bytownite rock C.71

The above rock has been observed at one point within the anorthosite belt, and was collected from an old corundum quarry. In view of its peculiar mineral assemblage and restricted occurrence, it has been interpreted as a xenolith. The rock is composed of a very fine grained aggregate of anorthite-bytownite, with several large crystals of cordierite and pinkish corundum developed in the feldspathic matrix. Anthophyllite crystals are distinguishable in hand specimens. The modal composition of the rock is as below and the density of the rock is 2.90 gm/cm^3 .

Plagioclase (An ₇₃₋₉₁)	30.2
Cordierite	30.8
Anthophyllite	4.0
Corundum	21.2
Clinozoisite	1.4
Scapolite	4.4
Calcite	2.0
Spinel	0.5
Sillimanite	5.0
Ores	0.5

The grain sizes of the various minerals are: Feldspar 0.5 mm. to 2 mm., cordierite, 1.4 mm. to 6 mm., corundum 1.8 mm. to 10 mm., sillimanite 0.5 mm. to 3 mm., anthophyllite 0.2 mm. to 2 mm.

Thin sections show crystalloblastic texture with a mosaic of calcic plagioclase in which larger grains of cordierite and corundum are embedded with apparent replacement relationship. Anthophyllite occurs as prismatic crystals within and outside the cordierites while aggregates of acicular sillimanite are distributed within larger cordierite and plagioclase crystals. Scapolite and calcite are secondary after the feldspar. A few grains of clinozoisite are scattered over the matrix, while green spinel

(pleonaste?) is seen intergrown with plagioclase. Plagioclase of two distinct compositions are noticed in this rock, grains in contact with corundum and occurring as insets in the corundum have an An content of 91% while the larger grains of feldspar away from the corundum have an An content of 73%. These variations were observed during the determination of twinning on the Universal stage and confirmed during index determinations by immersion. Both simple and complex twins of plagioclase were observed; the former in greater profusion. The scapolite secondary after the feldspar has 65% melanite, as indicated by the following values for $N_E=1.548$, and $N_O=1.576$. The cordierite present is a variety exceptionally rich in magnesia, as indicated by a chemical analysis. The mineral exhibits lamellar twinning, and though fresh, carried an abundance of sillimanite needles and other dusty mineral particles. The optical properties of the cordierite are: $N_X=1.539$, $N_Y=1.544$, $N_Z=1.546$; $2V=-66^\circ$. The anthophyllite is an aluminian variety as indicated by the value for $N_Z=1.658$, which is very close to that of the analyzed anthophyllite. Sillimanite is identified by its fibrous habit and low optic angle. A chemical analysis of this type has been made.

ECLOGITE-GABBRO SERIES

Rocks of a gabbroic and eclogitic types occur interbanded with the anorthosites, and also as conspicuous bands on the southern margins of the complex. The term eclogite-gabbro series has been adopted as a suitable name to designate this group. On the basis of petrographic examination, the following principal types have been recognized:

1. Eclogite-Bronzitic pyropite(Bronzitic pyralmanditite)
2. Bronzitic eclogite
3. Hornblende eclogite
4. Plagioclase eclogite

Eclogite has been defined by Johannsen (1937) as a rock composed of the grass green pyroxene, omphacite and pink garnets, probably metamorphic. This definition originally made in 1822 by Haüy has undergone considerable modification since then, following the studies on eclogites by Briere, Eskola, Hezner and many others. From strictly biminerallitic assemblages of pyroxene and garnet, the term has been extended to polymineralic assemblages, with plagioclase, amphiboles, kyanite and other minerals. Many authorities have considered omphacite a critical mineral for establishing a rock as eclogite. This, to the writer, appears inadequate as the precise status of omphacite among clinopyroxenes, and distinct properties to distinguish it from green diopside are yet to be fixed. In this connection Davidson's (1943) remarks are pertinent, and he writes with special reference to omphacite from eclogites of Rodil district as below:

"The following physical properties of the pyroxene have been determined $N_Y = 1.689$, $N_X = 1.687$, $N_Z = 1.704$, $N_Z - N_X = 0.024$, $Z \wedge c = 43^\circ (+)$ $2V = 64^\circ - 65^\circ$, $Sp.G. = 3.32$. No chemical analysis has been made, but two points are worthy of notice. Firstly, the alkalies of the eclogites are low, and the omphacite cannot therefore contain more than a small amount of the jadeite molecule. Secondly, the very low silica percentage of these rocks (40.78%, 42.66%) is not greatly in excess of that of the garnet (38.72%), and the omphacite may therefore, be presumed to be much poorer in silica than the pyroxenes from eclogites listed by Alderman (1936, pp. 495; 54.21-55.56% SiO_2). It appears probably that the greater part of the alumina in the pyroxene is present as Tschermak's silicate $[(MgFe)(AlFe)_2Si_6O_{18}]$ rather than as jadeite $[(NaK)(AlFe)_2Si_6O_{18}]$ or lime jadeite $[(CaMg)(AlFe)_2Si_4O_{12}]$. In this the mineral is similar to the pyroxenes of the Saxon pyroxene granulites described by von Philipborn (1930).

It may be noted that while in general composed dominantly of diopside + jadeite, the eclogitic pyroxenes recorded in petrographic literature have a wide range of composition. Eskola (1922) remarks that most of them contain an excess of alumina in addition to the alumina combined with the soda in the jadeite molecule and that they also show great variation in their CaO: (MgFe) O ratio, and also in the amount of silica. In all cases their composition may be expressed in terms of $\text{Ca}(\text{MgFe}) \text{Si}_2\text{O}_6$, $(\text{MgFe}) \text{SiO}_3$, CaSiO_3 , $(\text{NaK}) (\text{AlFe}) \text{Si}_2\text{O}_6$, $(\text{CaMgFe}) (\text{AlFe})_2 \text{Si}_4\text{O}_{12}$, and $(\text{CaMgFe}) (\text{AlFe})_2 \text{SiO}_6$. In the most basic rocks the proportion of jadeite and lime jadeite is almost always small; while chromic oxide also enters into varieties associated with chromiferous peridotites. It is questionable whether any special purpose is served by maintaining the name omphacite for a species of so considerable range in composition."

Eclogites are generally regarded to have a garnet rich in pyrope and almandite molecules, but no critical range has been fixed as to the composition, though suggestions have been made by Eskola (1921) and Herzsch (1927) and Wright (1938).

The modal mineralogical composition of these types together with the composition of the principal minerals in them are tabulated on the following page:

MODAL MINERALOGICAL COMPOSITION OF ECLOGITES

Minerals present	Bronzitic pyropite	Bronzitic eclogite	Hornblende eclogite	Plagioclase # eclogite
Quartz	+	+	+	1.5
Plagioclase	1.4	17.5	22.4	19.3
Clino-amphibole	2.2	16.3	25.3	12.0
Clino-pyroxene	5.8	7.1	4.4	7.0
Ortho-pyroxene	7.2	6.4	3.9	7.2
Garnet	72.4	39.8	31.2	32.3
Ores	1.2	1.6	1.2	1.5
Spinel	+	0.4	0.7	+
Scapolite	+	+	1.7	+
Kelyphite (Plag+Pyx) + Amp	9.8	10.9	9.2	19.2
Ortho-pyroxene	En% 84	86	86	84.5
Plagioclase	An% -	48-58	40-45	48-58
Garnet	*Mg% 55	51	50	46
Clino-pyroxene		Diopside-salite		
Density gm/cm ³	3.35	3.24	3.18	3.14

This rock has been analyzed and will be discussed in the next chapter.

* Expressed as ratio of mgO molecules according to Eskola (1921).

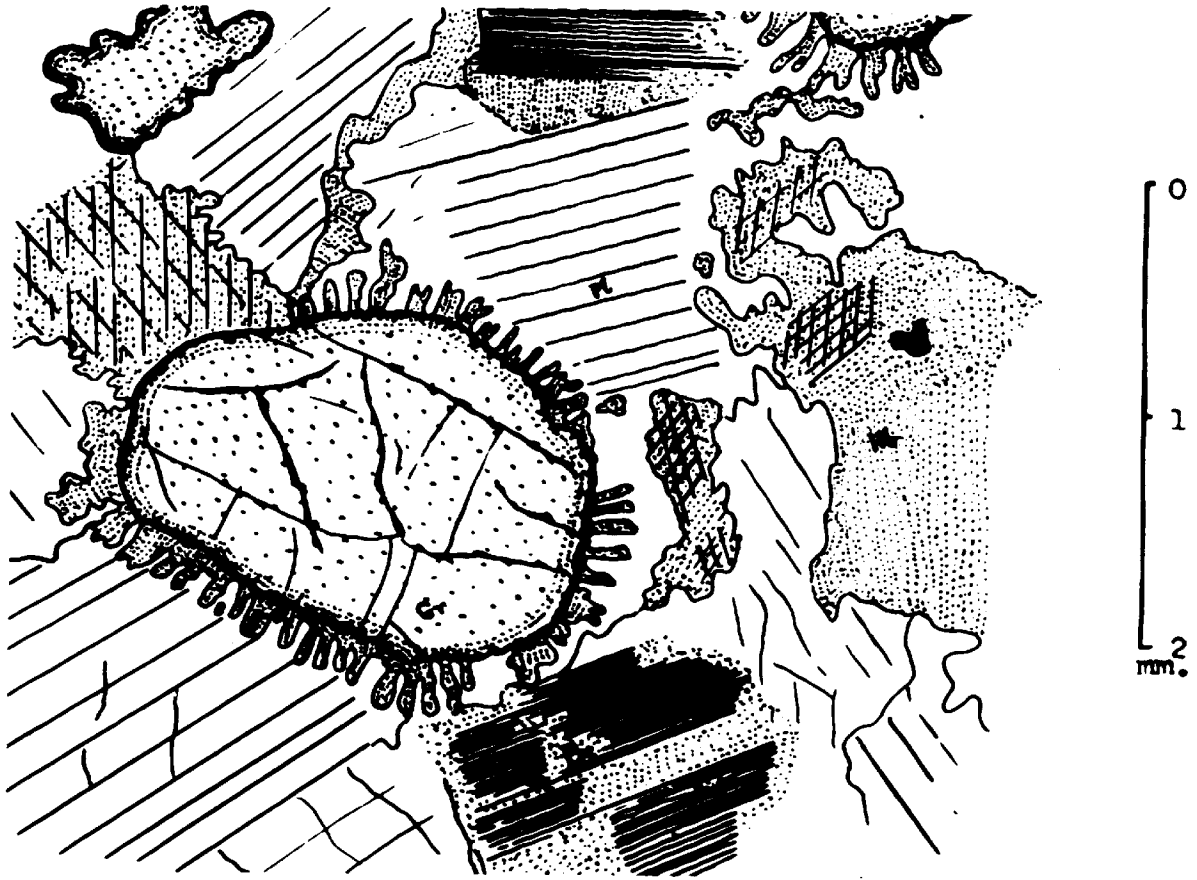
A review of the literature has shown the writer that true eclogite garnets are more pyropic while those in gabbros and granulites are almanditic. In the opinion of the writer, rocks described as eclogites and carrying almanditic garnets should be regarded with suspicion. This will be discussed in a later section. Petrographic descriptions of the principal types of eclogites follow.

Bronzitic pyropite

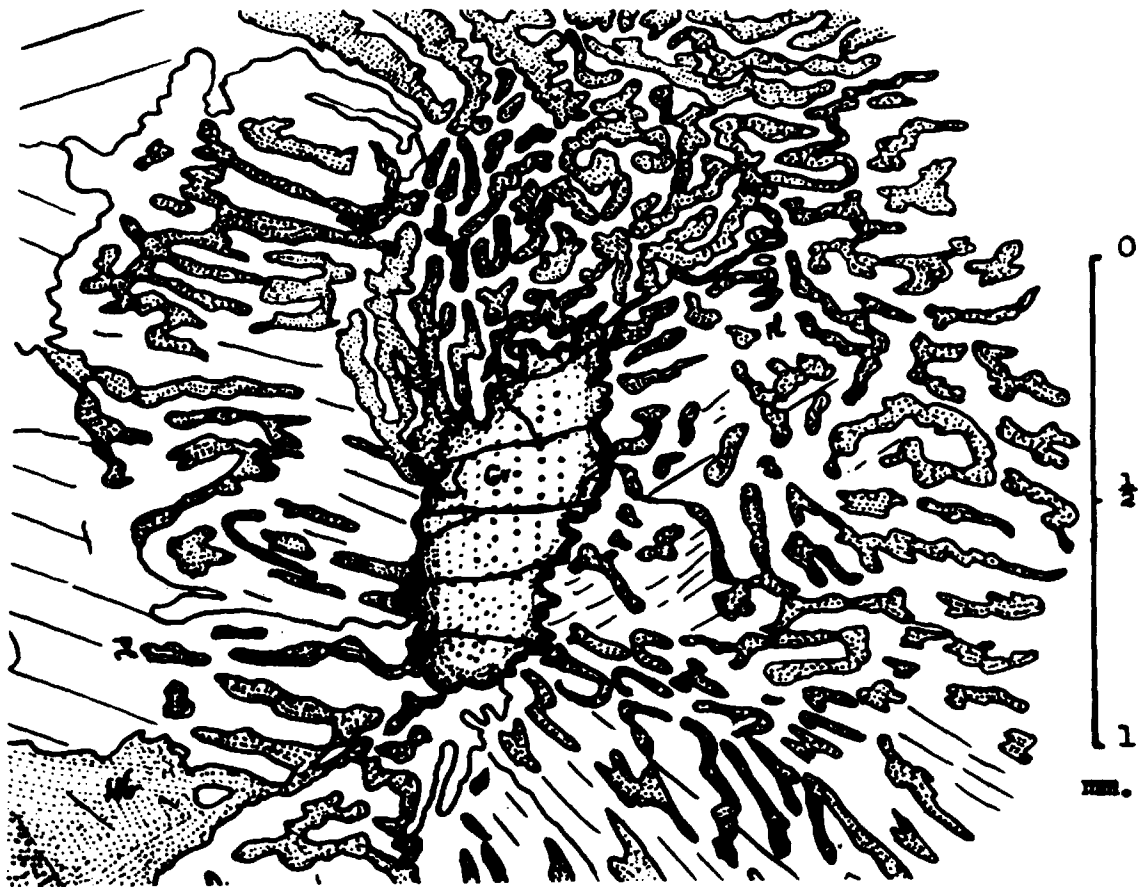
Hand specimens are green in color and studded all over with pinkish red grains of garnet. Weathered specimens in the field display on the surface only the garnets due to differential weathering, and give the impression that the rocks are entirely made up of garnet. Hand specimens have a holocrystalline texture and do not display any foliation. The density of this type is 3.35 gm/cm^3 .

Thin sections of this type show a remarkable texture, the rock being almost entirely composed of rounded grains of garnet with a very thin rim of kelyphite all round, and occasionally interstitial clino and orthopyroxenes. The garnets vary from 0.8 mm. to 4 mm. in diameter, and are characterized by a system of horizontal cracks. The optical properties of the various minerals in the rock are: Garnet: $N=1.754$; Orthopyroxene: $N_z=1.685$; Clinopyroxene: $N_x=1.680$, $N_z=1.710$, $2V = +59^\circ$, $2\wedge c=44^\circ$. The compositions of these minerals inferred from the above optical properties are shown in the tabular statement of the modes.

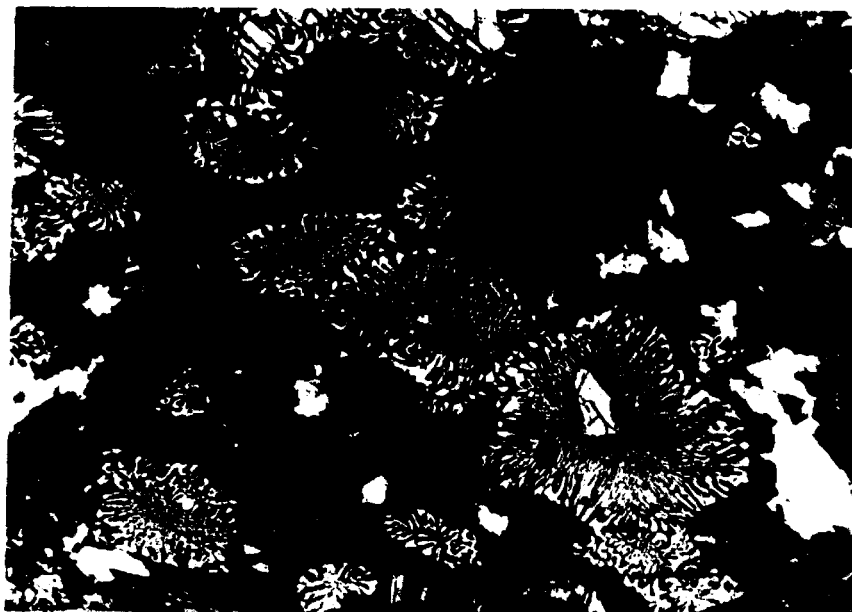
Thin sections of similar rocks have shown a much higher proportion of garnet than the rock described. In view of the preponderance of pyramanditic garnet in this rock, and the presence of bronzite, the name Bronzitic pyropite is suggested as it is felt that it is a rather unique



Bronzitic eclogite with corona around garnet. Note paramorphic alteration of bronzite to hornblende, and the plagioclase hornblende symplectite.

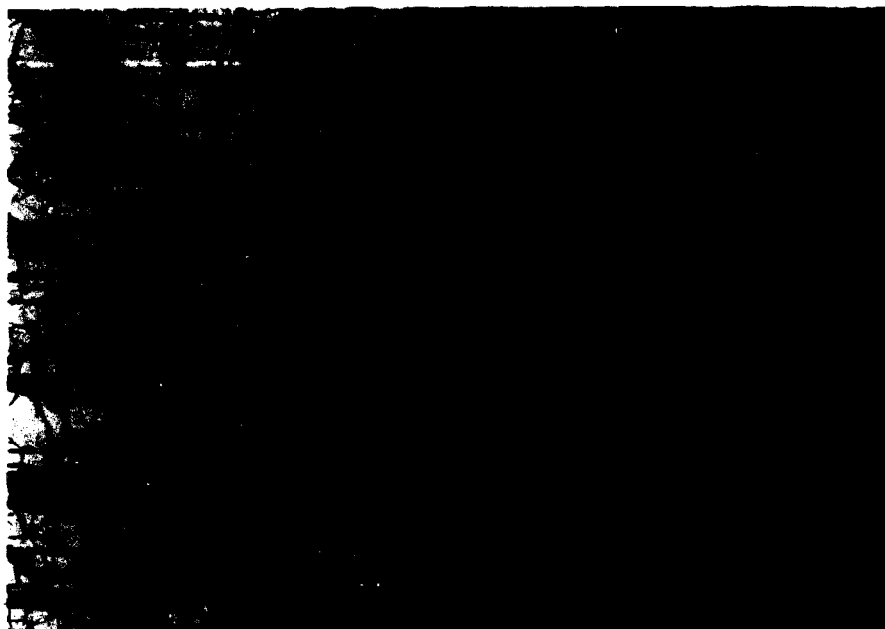


garnet crystals with symplectitic corona around them in eclogite. Note the zonal distribution of ores all round the garnet. Photomicrograph in Plate 35, brings this out clearly, and the above drawings are from the same thin section.



Garnets with symplectitic coronas in eclogite gabbro. Note zonal distribution of ores around the garnets.

X. 10



Bronzitic pyropite. Note that the rock contains mainly pyropic garnet and bronzite. Note the horizontal cracks in the garnet.

X. 15

petrographic type. The term "pyropite" is used instead of pyramanditite, the former being more euphonious.

Bronzitic eclogite

This type is characterized by a much lower proportion of garnet which is accounted for by the appearance of plagioclase and monoclinic amphibole. This variety has a fine grained texture and the garnets are not as conspicuous as in the type described above. The density of this type is 3.24 gm/cm^3 .

Thin sections display a granoblastic texture with rounded grains of garnet displaying kelyphitic coronas. The pyroxenes display paromorphic alteration to a greenish amphibole. The garnets in this rock range from 0.5 mm. to 2 mm in diameter, while the other minerals have an average grain size varying from 0.5 to 2 mm. The optical properties of the minerals present are: Garnet, $N=1.757$; Orthopyroxene, $N_z=1.682$, Clinopyroxene, $2V=+60^\circ$, Plagioclase, $N_x=1.553$, $N_z=1.561$. The compositions of these minerals conforming to the determined optical properties are indicated in the tabular statement of modes.

Hornblende eclogite

This type is very similar to the above, but there is a marked increase in plagioclase and amphibole and a commensurate decrease in the quantity of pyroxenes and garnet. The development of plagioclase hornblende symplectite around the garnets which was incipient in the type described before is fairly conspicuous here. Texture and mineral associations are similar to the former, but the plagioclase shows alteration to scapolite. The optical properties of the minerals present are: Garnet: $N=1.758$; Orthopyroxene: $N_z=1.682$, Clinopyroxene: $2V=+60$,

$Z \wedge c = 44^\circ$; plagioclase, $N_X = 1.550$, $N_Z = 1.556$. The modal composition and estimated composition of the various minerals are tabulated.

Plagioclase eclogite (Garnet hornblende plagioclase rock) C.41

This is perhaps the most abundant type of eclogite in the complex, and differs from the type described above in having a smaller content of amphibole. Weathered hand specimens show an incipient foliation and rounded grains of garnet standing out conspicuously. Thin sections display a crystalloblastic texture, the garnets occurring in a matrix of pyriboles and plagioclase. The progressive development of plagioclase symplectites from garnets are noticed in thin sections of this type.

The first stage in the paramorphic alteration of the garnet is the development of incipient kelyphitic rims, which gradually give way to wisps of green hornblende. The next stage is the development of radial hornblende crystals all around the garnet in a matrix of turbid plagioclase. The final stage is where the garnet is completely replaced by a vermicular intergrowth of plagioclase and hornblende. Some of these textural peculiarities have been illustrated in the accompanying photomicrographs and micrographs.

The grain size of the various minerals are: Garnet 0.2 mm. to 3.5 mm., plagioclase 0.5 mm. to 2 mm., orthopyroxene 0.5 mm. to 2.0 mm., clinopyroxene, 0.5 mm. to 2 mm., hornblende 0.2 mm. to 2 mm. The density of the rock is 3.14 gm/cm^3 . The optical properties of the various minerals present are: Garnet: $N = 1.762$; orthopyroxene: $N_Z = 1.683$; clinopyroxene: $N_X = 1.681$, $N_Z = 1.708$, $2V = +58^\circ$, $Z \wedge c = 43^\circ$; plagioclase, $N_X = 1.553$, $N_Z = 1.561$. The pyroxenes display peripheral alteration to amphibole, and

in some cases the transformation is complete. The plagioclases display strained extinction, as well as a thin rim of more calcic composition. Mr. J. R. Smith estimates the calcic rim to make up 22% of the total feldspar. In some feldspar grains bands of oriented inclusions are noticed and may represent liquid or gas inclusions. The inverse zoning due to the presence of a calcic rim has been recorded in some eclogites from Norway by Eskola (1921); from the eclogitic charnockites of Jeypore by Ghosh (1941). The only minor accessory mineral is magnetite which has a zonal distribution around the garnet symplectites and probably represents iron released during the formation of the symplectite from garnet.

RETROGRADE CHARACTERS OF THE ECLOGITIC ROCKS

Alderman (1936) and Davidson (1943) have deciphered the retrograde changes in eclogites by detailed petrographic examination. Some of their observations find a parallel in the eclogites of the Sittampundi complex. The retrograde features show incipient development in the bronzitic pyrope, become marked in the bronzitic eclogites and pronounced in the hornblende and plagioclase eclogites.

The first stage in diaphoresis is the paramorphic alteration of clinopyroxene to amphibole, and in the bronzitic pyrope, kelyphitic rims composed of a mesostasis of plagioclase, clinopyroxene and amphibole, are developed. The next stage is the development of green hornblende as wisps and vermicular intergrowths in plagioclase around the garnets marking the destruction of the garnet. This is discernible in thin sections

of bronzitic eclogite. In some cases the plagioclase-clinopyroxene stage is not discernible; Davidson (1943) attributes this to low alkali content and basic composition of the rock, and to the presence of hypersthene molecule in the clinopyroxene.

The garnet in the retrograde eclogites have exceptional symplectite rims consisting of wisps of green hornblende radially arranged around the garnets in a groundmass of plagioclase An_{48} , with a zone of granular ore all around. Davidson (1943) records the presence of iron ore in some of the eclogites from Rodil district and considers them to be released during the amphibolization of pyroxene. He also states that soda and lime released during the amphibolization of the pyroxene, might have reacted with the garnet to form kelyphite accompanied by separation of magnetite. This interpretation is applicable in the present instance as well.

Holland (1901) has regarded the reaction rim around garnets as representing a stage in the formation of garnet from the primary mafic minerals. Fermor (1912) on the other hand has expressed the view that kelyphitic rims are formed by the destruction of garnet under special conditions when there is gradual lowering of pressure accompanied by rapid reduction of temperature. Eskola (1920) discussing such structures in Norwegian eclogites, states:

In the igneous Norwegian eclogites the development often has been the following. When the crystallization of the garnet was completed and liquid magma was still present, the conditions of the amphibole facies set in and now hornblende and plagioclase crystallized directly from the magma around the garnet. The later may thus be an unstable relic if its field of stability does not continue into lower temperatures than that of pyroxene.

The above view is apparently based on a questionable assumption of garnet crystallizing out of a magma, and hence the whole interpretation is untenable. Buddington (1939) discussing corona structure in the Adirondacks, interprets them as having formed during the closing stages of deformation associated with regional dynamo-thermal metamorphism. Shand (1945) has proposed a theory which seems to fit in with petrographic details. He believes that the formation of corona takes place during thermal metamorphism when iron and magnesium ions, liberated from an iron rich olivine, react with anorthite of the plagioclase forming garnet or amphibole and spinel. He believes that the albite molecule left in the feldspar would redistribute itself in the feldspar frame-work. This explanation would hold good for the formation of primary garnet from an ultramafic plutonic rock, with a kelyphitic rim, but the formation of symplectites around the garnet seems to be a process related directly to change in T and P conditions.

PYROXENITE-WEBSTERITE

Two types of pyroxenites occur within the complex and are thought to be later intrusions. Both the types have an identical mineralogical composition, and can be considered to be websterites in view of their being composed of an equal proportion of monoclinic and orthorhombic pyroxenes. Granulitic websterite occurs more extensively than the coarse pegmatitic variety, which forms small lenticular bodies within the anorthosites.

Websterite pegmatite: Bimineralic, composed of coarse crystals of hypersthene and diopside, the average grain size being over 3 mm. The

The orthopyroxene is faintly pleochroic and the value for $N_z = 1.689$ indicates a composition 78.5% En. The clinopyroxene is a diallagic diopside with $N_x = 1.681$, $N_z = 1.709$, $2V = +56^\circ$, $Z \wedge c = 42^\circ$.

Websterite: This is an even grained greenish rock composed of fresh pyroxenes. Thin sections show a typical granulitic texture, the ortho and clinopyroxenes forming a matrix of interlocking grains in which occasional grains of chromite are scattered. The orthopyroxene is hypersthene pleochroic in pinks and greens, with 77% En as indicated by $N_z = 1.683$. The clinopyroxene is deduced to fall in the diopside-salite range, on the basis of the following optical properties. $N_x = 1.670$, $N_z = 1.699$, $2V = +60^\circ$, $Z \wedge c = 42^\circ$. The average grain size of the rock is 1.5 to 3 mm.

AMPHIBOLITES

At several points along the margins of the complex amphibolitic rocks are seen which have been interpreted as a remnant of the metasedimentary sequence in which the basic complex was emplaced. Hand specimens are melanocratic and show the preferred orientation of the amphiboles. The density of this type is 2.996 gm/cm^3 . Thin sections show a very fine grained granoblastic texture with an average grain size of 0.2 mm. Amphibole constitutes more than 50% of the rock and forms layers in a ground mass of mortarised plagioclase. The mode of a chemically analyzed specimen of amphibolite is shown below:

Plagioclase An ₄₂₋₄₅	22.6
Orthoclase	1.5
Clinopyroxene	18.6
Clino-amphibole	55.5
Calcite	0.9
Sphene	0.1
Ores	0.8

The plagioclase constituting the groundmass has a grain size varying between 0.2 mm. to 0.5 mm. The principal indices of refraction on cleavage fragments $N_X=1.552$ and $N_Z=1.559$, indicate the composition to be An_{42-45} . Undulose extinction due to strain and turbid alterations of the crystals are noticeable. In some of the other amphibolites examined the composition of the feldspar varied from An_{30} to An_{50} . The amphiboles are pleochroic in olive greens and appear to be mostly derived from clinopyroxene. The amphibole has $N_X=1.656$, $N_Y=1.666$, $N_Z=1.676$ and is negative with large optic angle. The clinopyroxene is identified as diopside from its optic angle of $+60^\circ$. Calcite seems to be secondary and forms granular aggregates, while a few lozenge-shaped grains of sphene are noticed in some amphibolites. A representative specimen on chemical analysis yielded a bulk composition incompatible with the composition of the other rocks of the complex, thus confirming that it is genetically unrelated to the complex.

CHEMICAL COMPOSITION WITH NORMATIVE AND MODAL MINERALOGICAL COMPOSITION
OF SOME ROCKS FROM THE SITTAMPUNDI COMPLEX

CONSTITUENT	1	2	3	4	5	6	7
SiO ₂	44.58	41.61	44.89	46.36	37.63	46.93	48.50
TiO ₂	0.06	0.06	0.05	0.03	0.00	0.12	0.63
Al ₂ O ₃	30.81	33.17	31.53	33.05	47.50	19.42	14.15
Fe ₂ O ₃	0.94	1.78	0.38	0.46	0.14	0.44	2.62
Cr ₂ O ₃	0.02	-	-	-	0.01	0.04	0.09
FeO	1.77	0.22	2.66	0.48	1.15	8.24	6.36
MnO	0.04	0.02	0.05	0.01	0.05	0.15	0.29
MgO	2.72	0.23	3.68	0.42	2.48	10.08	9.18
CaO	17.05	20.96	14.98	16.53	9.05	12.43	12.95
Na ₂ O	1.35	0.32	1.35	1.99	1.12	1.61	2.43
K ₂ O	0.07	0.05	0.05	0.04	0.03	0.04	0.29
P ₂ O ₅	0.00	0.01	0.01	0.01	0.01	0.00	0.02
H ₂ O+	0.58	0.97	0.68	0.30	0.66	0.74	1.27
H ₂ O-	0.06	0.20	0.11	0.04	0.07	0.12	0.13
CO ₂	-	0.51	-	-	-	-	0.95
Cl	0.01	0.00	0.00	-	0.01	0.02	-
F	0.01	0.01	0.01	-	0.00	0.01	-
Loss O for Cl+F	0.01	-	-	-	-	0.01	-
TOTAL	100.06	100.12	100.31	100.22	99.39	100.38	99.86

C.I.P.W. NORMS

Quartz	-	-	-	-	7.08	-	-
Orthoclase	-	-	-	-	-	-	1.67
Albite	7.60	-	11.53	15.98	9.43	13.62	20.44
Anorthite	77.84	88.96	73.95	80.90	45.04	45.04	26.69
Nepheline	2.13	1.42	-	0.43	-	-	-
Corundum	-	-	2.14	-	29.10	-	-
Wollastonite	-	3.36	-	-	-	-	-
(Calcium Orthosilicate)	-	0.86	-	-	-	-	-
Diopside { Wo En Fs	2.90 1.95 0.72	0.58 0.50 -	- - -	0.46 0.30 0.13	- - -	6.84 4.10 2.38	13.22 8.70 3.56
Hypersthene { En Fs	- -	- -	3.10 1.45	- -	6.20 1.98	4.50 2.51	6.60 2.77
Olivine { Fo Fa	3.36 1.57	- -	4.27 2.34	0.49 0.31	- -	11.62 7.55	2.24 5.32
Magnetite	1.39	0.70	-	0.70	0.23	0.70	3.71
Ilmenite	-	-	-	-	-	0.15	1.06
Haematite	-	1.28	-	-	-	-	-
Chromite	-	-	-	-	-	0.25	-
Calcite	-	1.10	-	-	-	-	2.10
Normative plagioclase	90 10	100 0	88 12	93.5 16.5	92.5 17.5	79 21	57 43

plagioclase (Albite%)	10	0	12	83.5 16.5	82.5 17.5	79 21	57 43
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MODES EXPRESSED AS WEIGHT PERCENTAGES
ON THE BASIS OF POINT COUNT ANALYSES OF 10000 POINTS

Quartz	-	-	-	-	-	1.5	-
Plagioclase	79.1	66.1	69.70	89.2	30.0	19.7	22.6
Orthoclase	-	-	-	-	-	-	1.5
Cordierite	-	-	-	-	30.8	-	-
Clinopyroxene	-	-	-	2.4	-	7.0	18.6
Orthopyroxene	-	-	-	-	-	7.2	-
Orthoamphibole	-	-	8.20	-	4.0	-	-
Clinoamphibole	20.9	-	21.80	5.3	-	12.0	55.5
Garnet	-	7.2	-	-	-	32.3	-
Corundum	-	-	-	-	21.2	-	-
(Clinzoisite Epidote)	-	21.1	-	3.1	1.4	-	-
Scapolite	-	4.2	-	-	4.4	-	-
Calcite	-	1.4	-	-	2.0	-	0.2
Spinel "	-	-	0.30	-	0.5	-	-
Ores	Tr	-	-	-	0.5	1.5	0.8
Sphene	-	-	-	-	-	-	0.1
Sillimanite	-	-	-	-	5.0	-	-
(Plagioclase+ Kelyphite (clinoamphibole+ (clinopyroxene)	-	-	-	-	-	19.0	-
Modal (Anorthite% Plagioclase (Albite%)	90-96 4-10	98-100 0-2	90-92 8-10	84-38 12-16	73-91 9-27	50-58 42-50	42-45 55-58
Density	2.825	2.934	2.833	2.751	2.904	3.139	2.996

EXPLANATION

- C.35 1) Anorthite hornblende gneiss, from old corundum quarries 1 mile south west of Sittampundi, Salem district, Madras India. Analyst: Eileen K. Celund, Minnesota
- C.50 2) Anorthite clinzoisite garnet rock, from old corundum workings 2 miles south of Konasamudram, Salem district, Madras India. Analyst: Eileen K. Celund, Minnesota
- C.69 3) Anorthite anthophyllite hornblende rock, simulating feather amphibolite, 3/4 mile west of Karungalpatti, Salem district, Madras India. Analyst: Eileen K. Celund, Minnesota
- C.128 4) Bytownite clinzoisite hornblende gneiss, from summit of small temple hill north of Kattipalaiyam, Salem district, Madras India. Analyst: Eileen K. Celund, Minnesota
- C.71 5) Cordierite corundum anthophyllite bytownite rock, 3/4 mile west of Karungalpatti, Salem district, Madras India. Analyst: Eileen K. Celund, Minnesota
- C.41 6) Garnet hornblende plagioclase rock (Eclogite?) from band, west of Sittampundi, Salem district, Madras India. Analyst: Eileen K. Celund, Minnesota
- C.45 7) Amphibolite, from outcrop on northern margin of anorthosite, 3/4 mile south of Konasamudram, Salem district, Madras India. Analyst: J. A. Maxwell, Minnesota

Table XXXI

ANALYSES OF ANORTHOSITES FROM SOUTH AFRICA, SWEDEN
AND SITTAMPUNDI COMPLEX

	1*	2	3	4**	5	6	7	8***	9	10	11
SiO ₂	48.90	48.25	47.48	48.62	41.61	46.86	44.58	48.85	43.49	48.19	44.89
TiO ₂	tr	0.05	tr	0.40	0.06	0.03	0.06	0.10	0.19	0.42	0.05
Al ₂ O ₃	30.00	30.60	32.34	28.77	33.17	33.05	30.81	26.45	29.27	26.54	31.53
Fe ₂ O ₃	0.50	0.90	0.70	1.27	1.78	0.46	0.94	0.45	0.79	0.99	0.38
Cr ₂ O ₃	-	-	-	0.00	-	-	0.02	-	-	0.18	-
FeO	1.30	0.95	0.38	1.44	0.22	0.48	1.77	2.15	2.61	3.22	2.66
MnO	0.00	0.00	0.19	0.06	0.02	0.01	0.04	-	0.03	0.06	0.05
MgO	0.55	0.65	0.38	1.42	0.23	0.42	2.72	4.25	4.50	2.59	3.68
CaO	16.90	17.75	16.00	14.10	20.96	16.53	17.05	14.05	15.06	13.99	14.88
Na ₂ O	1.95	0.60	1.92	2.64	0.32	1.99	1.35	2.10	1.24	2.50	1.35
K ₂ O	0.15	0.10	0.43	0.27	0.05	0.04	0.07	tr	1.09	0.35	0.03
P ₂ O ₅	tr	0.25	0.20	0.02	0.01	0.01		0.05	0.25	0.20	0.01
CO ₂	tr	-	0.04	0.65	0.51	-	-	tr	Σ = 0.05	0.05	-
H ₂ O+	0.10	0.25	0.23		0.97	0.30	0.58	0.15	1.37		0.68
H ₂ O-	0.10	0.15	0.04	0.40	0.20	0.04	0.06	0.10	0.13	0.71	0.11
Cl	-	-	-	-	0.00	-	0.01	-	-	-	0.00
F	-	-	-	-	0.01	-	0.01	-	-	-	0.01
(Ni,Co)O	-	-	0.02	-		less 'Cl'	0.01	-	-	-	-
						for F+Cl					
	100.90	100.50	100.35	100.18	100.12	100.22	100.06	100.70	100.07	99.99	100.31
Density	2.79	2.737	2.728	-	2.934	2.751	2.825	-	2.75	-	2.833
Modal											
Plagioclase	An ₈₃	An ₉₀	An ₈₀	An ₈₀	An ₉₈	An ₈₆	An ₉₀	An ₇₈	An ₈₀	-	An ₉₁
Approximate % of plagioclase	96	96	98	82	66	89	79	85	82	-	70

1,2,3 Anorthosite, from critical zone of Bushveld complex, quoted from Hall (1932) p. 334.

4 Anorthosite, Soutpansberg, quoted from Van Zyl (1950) p. 75.

5,6,7 Anorthosites C.50, C.128, C.33 from Sittampundi complex.

8 Anorthositic norite, main zone, Bushveld complex, quoted from Hall (1932) p. 334.

9 Anorthite gabbro north west of Edsvik Sweden, quoted from Johannsen (1937) p. 342.

10 Anorthosite gabbro, Mossina, quoted from Van Zyl (1950) p. 75.

11 Anorthosite C.60 Sittampundi complex.

* Summation = 100.45

** Summation = 100.6

*** Summation = 99.70

Table XXXII

CHEMICAL COMPOSITION OF ECLOGITE GABBRO C.41
TOGETHER WITH COMPARABLE ANALYSES

B

	1	2	3	4	5	6	7	8	9
SiO ₂	46.93	47.35	47.50	47.00	50.75	52.05	48.02	46.49	48.16
TiO ₂	0.12	0.21	1.03	1.00	0.12	0.21	0.23	1.17	0.76
Al ₂ O ₃	19.42	16.72	17.14	17.61	20.02	17.24	20.01	17.73	19.66
Fe ₂ O ₃	0.44	0.34	2.00	2.25	0.42	0.65	1.13	3.66	1.53
Cr ₂ O ₃	0.04	-	-	-	-	-	0.03	-	-
FeO	8.24	6.91	6.04	6.78	3.87	6.65	7.29	6.17	5.06
MnO	0.15	-	-	-	0.05	0.13	0.18	0.17	0.14
MgO	10.08	12.42	10.37	8.78	9.34	8.98	10.05	8.86	7.53
CaO	12.43	14.09	13.61	14.90	13.07	11.37	11.42	11.48	13.46
Na ₂ O	1.61	1.42	1.42	1.14	1.14	1.83	0.51	2.16	1.88
K ₂ O	0.04	0.20	0.23	0.21	0.15	0.40	0.05	0.78	0.11
F ₂ O ₅	0.00	0.01	0.14	0.40	tr	0.12	tr	0.29	0.11
H ₂ O+	0.74	0.22	0.19	0.40	0.70	0.52	0.57	1.04	1.43
H ₂ O-	0.12	-	0.02	-	0.50	0.11	0.10	-	9-0.08
Cl	0.02	-	-	-	-	-	CO ₂ =0.25	-	-
F	0.01	-	-	-	-	-	S=0.02	-	-
							SiO=0.01	-	-
							V ₂ O ₅ =0.02	-	-
Less O									
Cl+F	0.01	-	-	-	-	-	-	-	-
	100.38	99.89	99.69	100.47	100.13	100.26	99.89	100.00	100.22
Density	3.139	3.383	3.36	3.01	3.386	2.965	2.98	-	-

1 Hornblende garnet plagioclase rock (eclogite gabbro) Sittampundi complex

2 Plagioclase eclogite quoted from Marchet (1924) p.313

3 & 4 Kyanite eclogite and garnet amphibolite quoted from Briere(1920) p.127 & 168

5 Kyanite eclogite, quoted from Tilley (1937) p.430

6 Common Norite of the Bushveld, quoted from Hall (1932) p.350

7 Norite from Maryland quoted from Johannsen (1937) p.220

8 Daly's average of 17 olivine gabbros, Johannsen (1937) p.222

9 Noritic hornblende gabbro quoted from Miller (1937) p.1412

CHEMICAL GEOLOGY AND METAMORPHISM

The chemical composition of some of the significant minerals from rocks of this complex, and their bearing on the chemistry of these rocks have been discussed in Chapter III. An attempt will be made here to discuss the chemistry of the rocks and interpret their probably metamorphic transformations.

The chemical composition together with the normative and modal mineralogical composition of the various analyzed rocks of the complex are presented in Table XXX. In Table XXXI, the analyses of the anorthositic rocks from the complex with comparable analyses of anorthosites from South Africa and Sweden are tabulated. In Table XXXII, the analysis of eclogite from this complex together with comparable analyses of rocks from other parts of the world are tabulated

Anorthosite series: The rocks of the anorthosite series are undersaturated and extremely rich in alumina. The presence of corundum and calcic plagioclase indicate the aluminous nature of these rocks while normative nepheline and calcium orthosilicate point to the poverty in silica. While the impoverishment in silica may be attributed to removal during metamorphism, it is difficult to explain the high alumina content, except by making an assumption that the rocks were derived from a magma enriched in alumina. As already mentioned previously the mineralogy of the rocks indicate their being rich in 'OH' molecule, and in Chapter III several chemical reaction are postulated to derive an 'OH' rich paragenesis. It is postulated here that these rocks have been subject to chemical readjustment during regional metamorphism, accentuated during the intrusion of a later granite, which must have supplied adequate amounts

of volatiles and water. It is thought that these moved into the intergranular spaces of the anorthositic rocks and actuated chemical reactions, resulting in the formation of corundum, clinozoisite, edenite, and other minerals.

It is possible to infer two periods of chemical transformations in these rocks on the basis of their paragenesis. The first stage is interpreted to have resulted in the formation of amphiboles from the primary pyroxenes and olivine, with some of the albite molecule of the plagioclase entering the amphibole framework, as indicated by the composition of the amphiboles. Recrystallization and foliation is thought to have been induced at this stage. These changes can be interpreted as having taken place, during the Archaean regional metamorphism characterized by intense migmatization and formation of Peninsular gneiss. This interpretation is on the basis of the fact that corundum, clinozoisite and garnet are definitely of later origin, as proved by their replacement relationship with anorthite and sometimes the amphibole. The preservation of skeletal diopside crystals interstitially among the feldspars, and their paramorphic alteration to amphibole seen in a few thin sections is thought to be a relict structure.

The second stage in the transformation of these rocks is correlated with the intrusion of the younger granites, which must have supplied the mineralizers. It is thought that these changes were induced under conditions of limited supply of H_2O and CO_2 , as otherwise the transformations would have been complete, and the resulting rocks would have been clinozoisite-corundum assemblages.

Epidote plagioclase equilibrium: Ramberg (1944) states that under conditions of regional metamorphism temperature influences the equilibrium more than pressure, resulting in progressive enrichment in anorthite by increasing metamorphic grade. He further states:

But because of the small difference in the chemical composition of anorthite and zoisite the equilibrium: plagioclase $\rightleftharpoons$ zoisite is not only dependent on P T - conditions. The average composition of the paragenesis plays a role. In supersilicified and H₂O-saturated rocks only the ratio Ca/Al effects the equilibrium at constant P and T. Since the Ca/Al ratio is greater in zoisite than in anorthite, Ca-rich environments in the pore liquid will displace the equilibrium towards zoisite and albitic plagioclase. Al-rich environments, on the other hand, will displace it towards anorthitic plagioclase.

Petrographic experience seems to prove that the difference in the Ca/Al ratios of the common minerals: Garnet, hornblende, biotite and diopsidic pyroxene has no important effect on the equilibrium plagioclase $\rightleftharpoons$ zoisite. That is to say, that the composition of the plagioclase which is in stable equilibrium with zoisite in common rocks is principally determined by the P T conditions.

In the present instance we have a group of rocks extremely rich in alumina as indicated by the corundum-anorthite-clinozoisite paragenesis. This seems to offer support to Ramberg's hypothesis that the plagioclase zoisite equilibrium will tend towards anorthitic plagioclase under Al rich environment.

Ramberg (1943) considers the epidote minerals to have a wide stability range, and hence plagioclases associated with epidote minerals become increasingly basic at elevated temperatures. He also considers that stable associations of plagioclase and epidote minerals are governed by equality in their pressures, which in turn is governed by P , T conditions.

Ramberg considers grossularite, rich in pyrope and almandite to indicate high pressure, and vesuvianite, high temperature.

If Ramberg's assumptions are correct the anorthositic rocks in this complex on the basis of their paragenesis, indicate a facies formed at elevated temperatures and pressures.

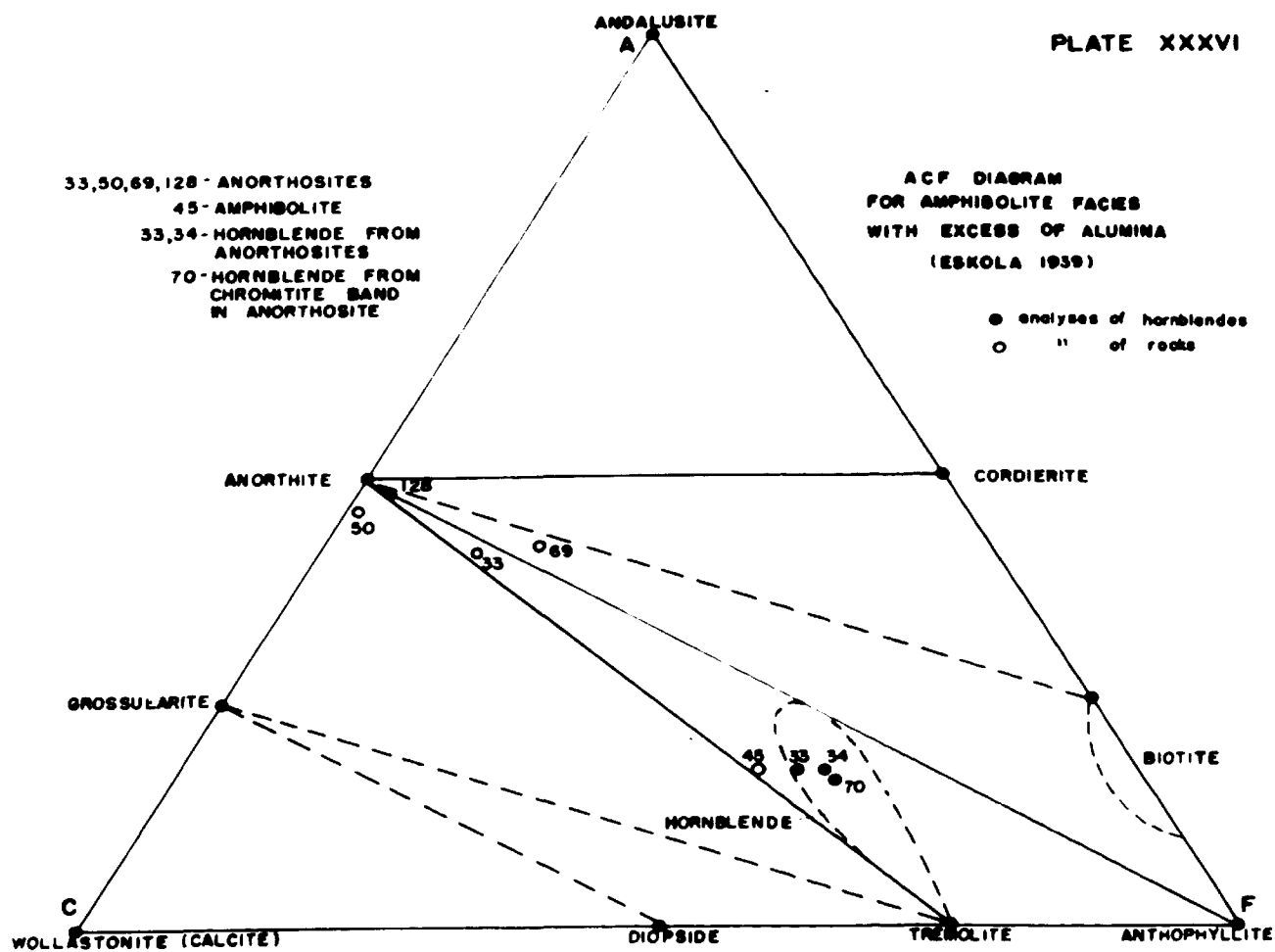
Metamorphic facies: An A C F diagram of Eskola (1939) for amphibolite facies with excess of alumina is shown on Plate 36. The analyzed anorthositic rocks and amphiboles as also an analysis of amphibolite from the area are plotted therein. The values used in the plot are shown below:

<u>Rocks</u>	A	C	F	
C.33	41.8	44.6	13.6	} Anorthositic Rocks
C.50	46.4	52.5	1.1	
C.69	42.3	38.8	18.9	
C.128	48.4	48.7	2.9	
C.45	17.5	32.5	50.0	Amphibolite
<u>Amphiboles</u>				
C.33	17.1	29.4	53.5	from anorthosite
C.34	17.4	26.9	55.7	" "
C.70	16.2	26.7	57.1	from chromitite

It may be seen from the diagram that the hornblendes fall in the field defined by Eskola. The anorthositic rocks lie in the anorthite cordierite anthophyllite and anorthite wollastonite anthophyllite fields. Eskola (1915) has stated that anthophyllite plagioclase paragenesis has not been recorded, and instead, cummingtonite anorthite paragenesis is

ACF DIAGRAM
FOR AMPHIBOLITE FACIES
WITH EXCESS OF ALUMINA
(ESKOLA 1939)

- analyses of hornblendes
- " of rocks



formed. We have in the anorthositic rocks of this complex anorthite anthophyllite edenite pragensis, and as may be seen from the plot, two of the rocks fall in the vacant field indicated by Turner (1949) for the cordierite-anthophyllite subfacies.

Cordierite-corundum, anthophyllite-anorthite-bytownite rock: This is a peculiar assemblage found at one place within the anorthosites, and is interpreted as a xenolith or argillaceous sediment. Thomas (1922) has described a similar paragenesis occurring as xenoliths in the tertiary intrusions at Mull. He considers them modifications of more or less pure aluminous sediments by reaction with the magma and particularly by diffusion of lime, ferrous iron and magnesia. The formation of cordierite corundum paragenesis is attributed by Thomas to addition of magma in a modified form with enrichment of magnesia and alkalis and concomitant separation of corundum and acid plagioclase. The occurrence of plagioclase of two different compositions An_{71} and An_{91} lend support to the view of Thomas. He has also stated that the magma itself is not modified by the assimilation of sedimentary material.

Plate 37 shows the A C F diagram of Eskola (1939) for the sanidinite facies with the plot of the above rock whose values are: $A=65.1$, $C=23.5$, $F=11.4$. It may be seen that the rock falls in the anorthite-sillimanite cordierite field. The absence of sanidine can be attributed to the poverty of alkalis in the original magma. Thomas has fixed the temperature of metamorphism at $1250-1400^{\circ}\text{C}$, by comparison with the known stability ranges of similar phases in investigated systems. Turner (1949) considers this rather excessive in view of the fact that basaltic magmas are not known

SILLIMANITE
A

PLATE XXXVII

ACF DIAGRAM
FOR SANIDINITE FACIES
(ESKOLA 1939)

71
CORUNDUM CORDIERITE
ANTHOPHYLLITE, ANORTHITE
SILLIMANITE, SPINEL, ASSEMBLAGE

71
O

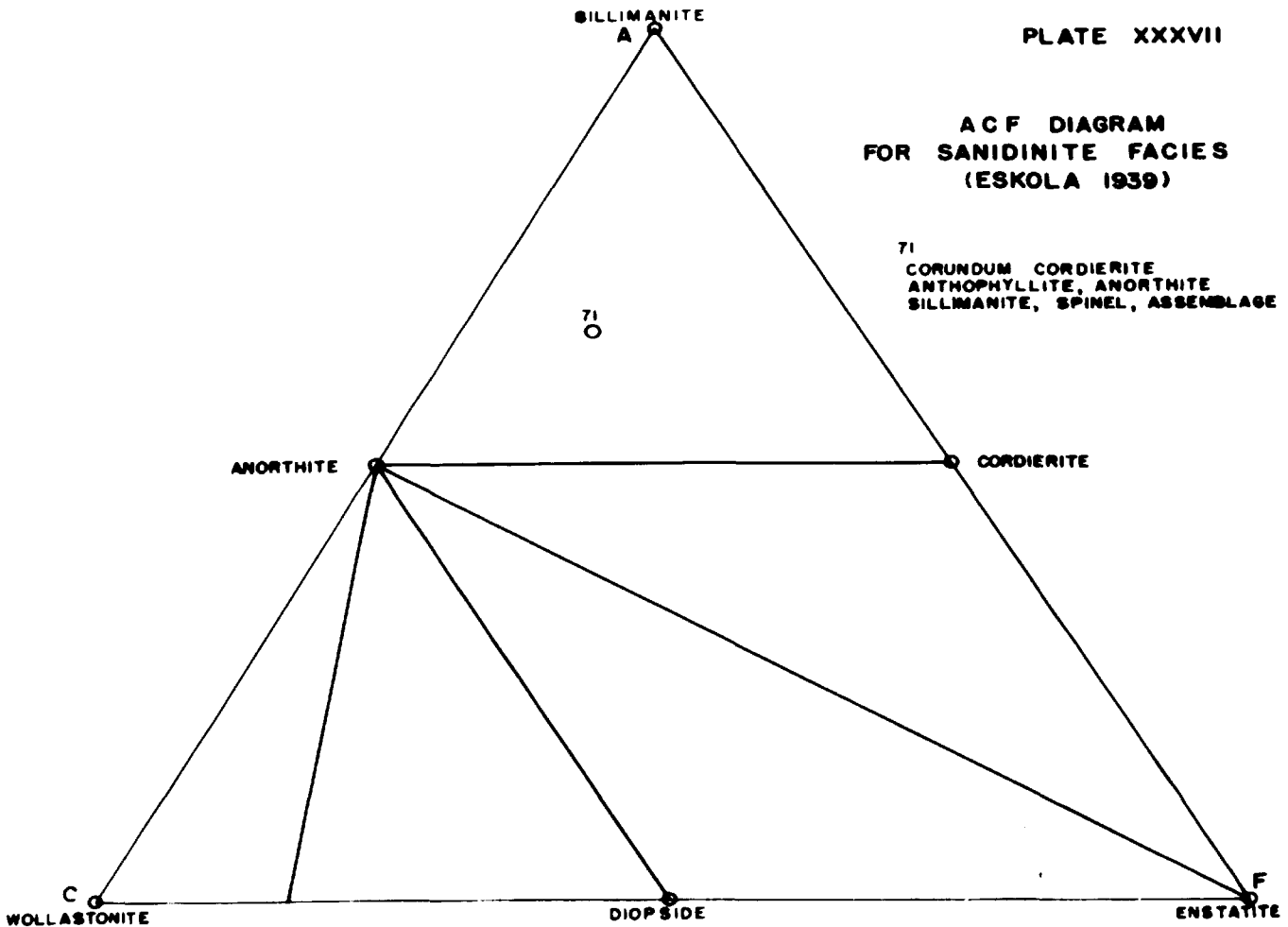
ANORTHITE

CORDIERITE

C
WOLLASTONITE

DIOPSIDE

F
ENSTATITE



to attain such temperatures. However, our knowledge of temperatures of magmas at depths below the surface is indefinite, and the interpretation of Thomas is tenable until more definite data are presented on magmatic temperatures.

PROBLEM OF THE ECLOGITES

A brief summary of the present status of the eclogite problem will be presented before entering into a discussion on the eclogites of the Sittampundi complex. As pointed out earlier, the significance of the original definition of eclogite has undergone modifications in the light of work by Briere, Høzner, Eskola, and several others. The green clinopyroxene omphacite which is considered a critical mineral in eclogites has been shown by Davidson (1943) to be of rather extensive compositional range.

Yoder (1950) has presented an admirable summary of the observations of various authorities on the eclogite problem, and some of the major trends of thought are presented here to help in a proper appreciation of the problem in so far as it applies to our rocks. Eskola (1922) has classified the eclogites into four types according to their mode of occurrence.

1. Inclusions in kimberlites, basalts and garnet bearing ultramafic rocks, with a paragenesis indicative of deep seated igneous or metamorphic origin.
2. Streaks and bands in dunites and related rocks, passing into garnetiferous granulites.
3. Lenticular bands in migmatized gneisses, interpreted as fragments from deep seated masses moved upward into geosynclines by intrusive granites. These eclogites show retrograde metamorphism induced by the granite and consequent migmatization.
4. Bands in rocks of a lower facies in highly folded tectonic zones.

Yoder (1950) has outlined six principal schools of thought on the genesis of eclogites and they are:

1. Direct crystallization from a magma under hydrostatic pressure.
2. High grade metamorphism of igneous and sedimentary rocks.
3. Metasomatism of sedimentary or igneous rocks.
4. Dynamic metamorphism of pre-existing rocks.
5. Hydrothermal contact metamorphism.
6. Migmatization or diatectic metamorphism.

The high density of eclogites as compared with rocks of similar bulk composition, as also the presence in them of minerals like diamond, kyanite, and rutile with high densities lead adherents of the first two schools of thought to postulate the formation of eclogites at high temperatures under very high confining pressures. The deep seated source of these rocks has been accepted without reservations by several petrologists on the basis of the occurrence of eclogite inclusions in kimberlites. The formation of retrograde characters like the paramorphic alteration of pyroxenes to amphibole, kelyphitic rims around the garnets, and the plagioclase hornblende symplectites, are interpreted to indicate a sudden lowering of pressure. The peculiar paragenesis and high density of the eclogites is interpreted as positive evidence of a very high pressure environment. The relatively small size of eclogite bodies, the paucity of minerals rich in 'OH' molecule, and the granulitic texture are interpreted as indicative of their origin in a high temperature, high temperature environment. Yoder has critically examined these concepts and considers many of them untenable.

Some workers have invoked metasomatism to explain the origin of

eclogitic rocks. Ghosh (1941) has considered the eclogites in the charnockite series of Bastar state, to be formed by complex metasomatism of impure calcareous sediments rich in magnesia and iron. In the absence of critical chemical and mineralogical data this interpretation has to be accepted with reservations though Davidson (1943) has rejected it. Dull (1902) and Rama Rao (1945) also consider metasomatism a potent factor in the production of eclogites.

Groves (1935) has advocated dynamic metamorphism to explain the origin of eclogites, but many other petrologists consider it as among one of the factors in the formation of eclogites. The writing of Hezner (1903) Briere (1920), Eskola (1939) and Kranck (1935) are significant in this connection.

The Russian school of petrologists consider eclogites as products of contact metamorphism Yoder (1950). Further, Korjinsky (1937) has proposed that eclogites have originated at moderate depths, citing the paucity of these rocks in pre-cambrian shield areas.

Backlund (1936), Kranck (1935), Weiseneder (1937) and several others have considered migmatization under extremes of pressure and temperature conditions as a potent factor in the production of eclogites. Dengo (1950), in discussing the eclogites of Venezuela which are associated with rocks of a lower facies, has postulated their origin as a metastable association formed as a step in the change of basic igneous rocks to amphibolites. This hypothesis is founded on the analogy to the metastable formation of anthophyllite, experimentally demonstrated by Bowen and Tuttle (1949), and the concept of metastable formation of kyanite suggested by Riddle and Foster (1949).

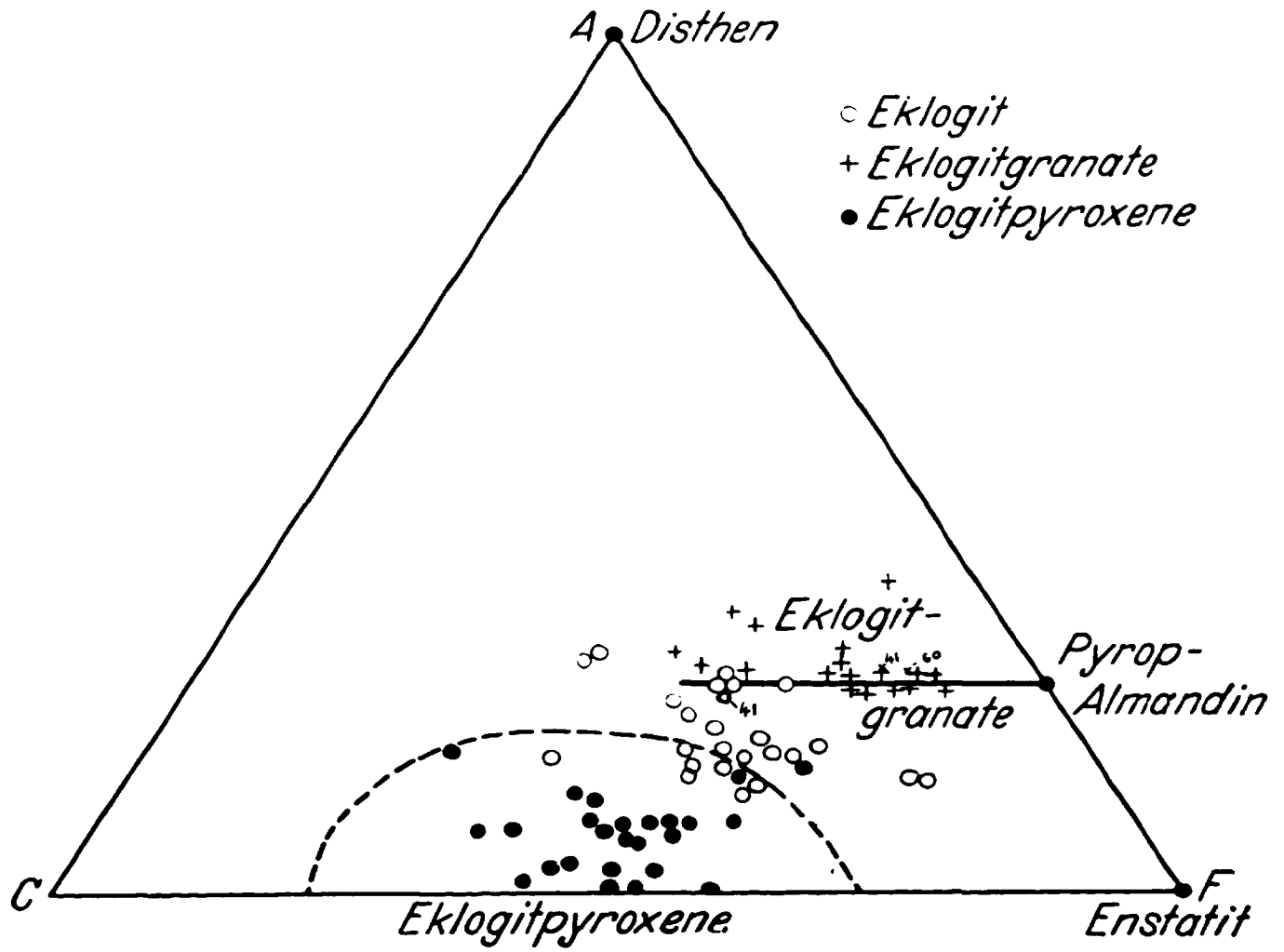
It may be seen from the above sketchy review of the problem that no satisfactory explanations have been offered so far supported by critical field and laboratory evidence. Yoder (1950) in summarizing the problem has expressed his own opinion that the small amount of soda commonly found in eclogite pyroxene does not justify the assignment of special conditions for its formation.

ECLOGITE ROCKS OF SITTAMPUNDI COMPLEX

The eclogites of the Sittampundi have already been described in the previous chapter, and the principal types are:

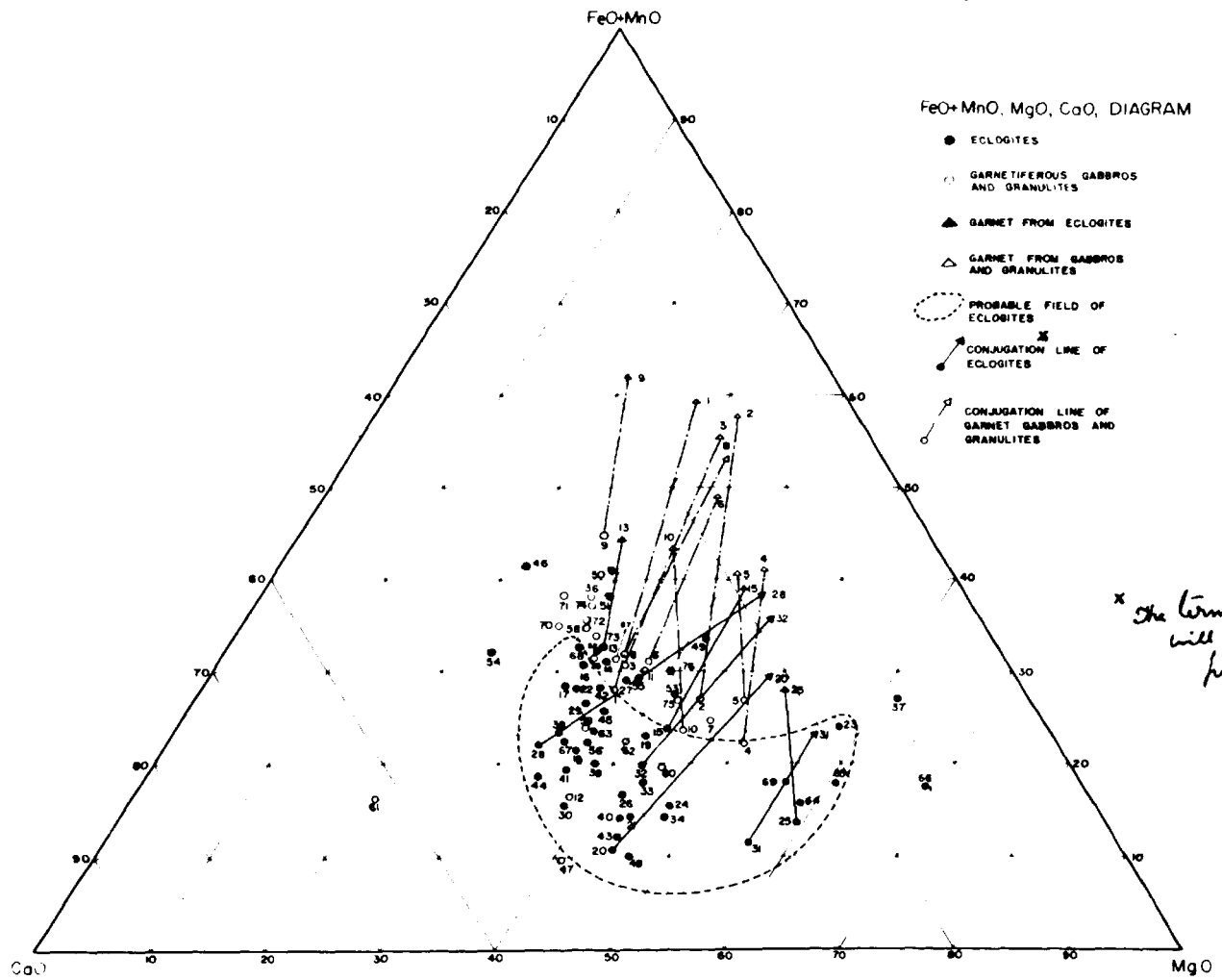
1. Hornblende eclogite
2. Plagioclase eclogite
3. Bronzitic eclogite
4. Bronzitic pyropite

The first two types form fairly conspicuous in the southern portion of the complex, becoming increasingly hornblendic towards the junction with the migmatized gneisses and amphibolites. Types 3 and 4 are associated with the anorthosites in which they form irregular bands and lenticular bodies, varying in length from 15 to 100 yards and in width from 5 to 20 yards. Peripheral transformation to types 1 and 2 are noticeable in some of these bands. The above mode of occurrence is very similar to that of the eclogites of Rodil district described by Davidson (1943). Foliation is noticeable in types 1 and 2 conforming to the prevalent foliation of the rest of the complex. Types 3 and 4 show a system of joints conformable to those noticed in the anorthosites and related chromitites. The field relations point to these eclogitic rocks being comagmatic with the anorthosites.



ACF-Diagramm der Eklogitfazies.

PLATE XXXIX



The A C F values for an analyzed eclogite and two analyzed garnets from these rocks are:

	A	C	F
Rock C.41	21.8	29.4	48.8
Garnet from above rock	25.7	13.7	60.6
Garnet from bronzitic pyro- pite C.60	25.1	10.7	64.2

In Plate 38, these values are shown in the A C F diagram of Eskola (1939) for the eclogite facies. It may be seen that the rock and the garnets, fall in a zone characteristic of eclogites.

(FeO+MnO), MgO, CaO, MOLECULAR DIAGRAM

Professor Buddington has used for the Adirondack metagabbroic rocks a diagram to express the relationship of minerals to the rocks containing them in which the molecular ratios of (FeO+MnO) MgO, and CaO are represented in the three corners of a conventional triangular diagram and the composition of the rock and the mineral from the same rock plotted. The two plotted points are connected by a tie line which indicated the trend in change of the composition of the rock in relation to the containing mineral. The lines constructed by the author on the basis of plots for garnetiferous gabbros and amphibolites, and eclogites brought out a very striking peculiarity. It has been found that while in the case of gabbroic rocks the garnets were less magnesian than the rocks; in the eclogites the garnets were more magnesian than the rocks. This is brought out clearly in the diagram, where the tie lines for the two types trend in different directions. The chemical composition of 76 eclogites, garnet, gabbros, garnet amphibolites and from the literature, have been plotted in the diagram shown in Plate XXXIX. It was found

Table XXXIII

MOLECULAR RATIOS (FeO+MnO), CaO, AND MgO OF GABROIC AND ECLOGITIC ROCKS
TOGETHER WITH THOSE OF THE GARNETS IN THEM INSOFAR AS AVAILABLE,
RECALCULATED TO 100%

	ROCK				GARNET		
	(FeO+MnO)	MgO	CaO		(FeO+MnO)	MgO	CaO
1	28.0	36.0	36.0	Reconstituted gabbro	59.4	27.5	13.1
2	27.0	44.0	29.0	" "	57.9	31.8	10.3
3	30.4	35.6	34.0	" "	55.6	31.6	12.8
4	22.3	50.0	27.7	" "	41.2	42.5	16.3
5	27.0	48.0	25.0	" "	40.7	40.3	19.0
6	31.0	37.5	31.5	" "	49.0	34.4	16.6
7	24.5	46.2	29.3	Garnet metagabbro	-	-	-
8	31.7	35.0	33.3	Eclogite hornblende gabbro	53.0	33.0	14.0
9	45.1	28.4	26.5	Garnet gabbro	62.0	20.0	18.0
10	23.8	44.0	32.2	Hypersthene garnet granulite	43.4	33.5	23.1
11	30.0	37.7	32.3	Garnet amphibolite	-	-	-
12	16.2	38.0	45.8	" "	-	-	-
13	32.6	32.7	34.7	Eclogite	44.2	28.6	27.2
14	31.0	33.8	35.2	"	-	-	-
15	23.6	43.0	33.4	"	38.9	41.9	19.2
16	30.6	32.0	37.4	"	-	-	-
17	28.3	31.5	40.2	"	-	-	-
18	21.2	46.0	32.8	"	-	-	-
19	23.0	41.4	35.6	Kyanite garnet amphibolite	-	-	-
20	10.4	44.8	44.8	Kyanite eclogite	29.4	48.9	21.7
21	14.2	44.2	41.6	" "	-	-	-
22	28.0	32.5	39.5	Eclogite	-	-	-
23	24.0	57.8	18.2	"	-	-	-
24	15.2	37.7	47.1	Garnet-pyroxene-labradorite rock	-	-	-
25	13.8	59.1	27.1	Eclogite	28.0	51.0	21.0
26	16.7	42.3	41.0	Amphibole eclogite	-	-	-
27	29.2	36.4	34.4	" "	-	-	-
28	22.2	32.3	45.5	Garnet gabbro	38.0	44.0	18.0
29	26.4	34.2	39.4	Eclogite	-	-	-
30	15.3	46.8	37.9	"	-	-	-
31	11.6	36.3	32.1	"	23.2	56.1	20.7
32	19.7	42.3	37.8	Eclogite gabbro	33.7	43.9	18.4
33	18.0	43.3	38.7	Garnetiferous-hornblende granulite	-	-	-

32	19.7	42.5	37.8	Eclogite gabbro	35.7	45.9	13.4
33	18.0	43.3	38.7	Garnetiferous-hornblende diopside hypersthene rock	-	-	-
34	14.5	47.2	38.3		-	-	-
35	31.6	32.2	36.2	Garnet amphibolite			
36	38.0	28.9	33.1	" "			
37	27.4	61.3	11.3	Eclogite			
38	23.3	33.6	43.1	"			
39	20.0	41.8	38.2	"			
40	14.0	43.6	42.4	"			
41	19.4	36.0	44.6	"			
42	28.2	34.7	37.1	"			
43	12.0	44.1	43.9	"			
44	18.3	34.0	47.7	"			
45	25.7	36.3	38.0	"			
46	41.5	21.3	37.2	"			
47	9.7	40.7	49.6	"			
48	10.2	46.2	43.8	"			
49	33.5	25.4	41.1	"			
50	40.9	29.0	30.1	"			
51	38.0	30.4	31.6	"			
52	32.5	34.9	32.6	"			
53	27.4	30.9	41.7	"			
54	32.0	23.0	45.0	"			
55	29.1	33.3	37.6	"			
56	22.3	41.1	36.3	"			
57	31.4	34.3	34.3	Garnet amphibolite			
58	34.7	30.0	35.3	" "			
59	23.8	35.3	40.9	" "			
60	19.6	36.2	44.2	" "			
61	16.1	21.0	62.9	" "			
62	22.3	38.0	39.7	" "			
63	23.6	36.0	40.4	Garnet norite			
64	15.8	58.5	25.7	Drusite (Eclogite)			
65	17.8	60.8	21.4	" "			
66	17.5	68.9	13.6	" "			
67	22.2	34.7	43.1	" "			
68	32.5	30.6	36.9	" "			
69	18.0	56.0	26.0	Hornblende eclogite			
70	35.00	27.6	37.4	Hyperite			
71	38.5	26.3	35.2	"			
72	35.4	29.8	34.8	"			

62	22.3	38.0	39.7	"	"
63	23.6	36.0	40.4	Garnet norite	
64	15.8	58.5	25.7	Drusite (Eclogite)	
65	17.8	60.8	21.4	"	"
66	17.5	68.9	13.6	"	"
67	22.2	34.7	43.1	"	"
68	32.5	30.6	36.9	"	"
69	18.0	56.0	26.0	Hornblende eclogite	
70	35.00	27.6	37.4	Hyperite	
71	38.5	26.3	35.2	"	
72	35.4	29.8	34.8	"	
73	34.0	30.7	35.3	"	
74	37.1	29.1	33.8	"	
75	27.0	41.8	31.2	Hornblende hyperite	
76	30.0	40.0	30.0	"	"

-
- 1-6 Reconstituted gabbros from the Adirondacks, quoted from the forthcoming paper by A. F. Buddington.
- 7 Garnet bearing metagabbro, quoted from Buddington (1939) p.60
- 8 Eclogite hornblende gabbro, quoted from Eskola (1921) p.43-44
- 9 Garnet gabbro, quoted from Eskola (1921) p.88
- 10 Hypersthene garnet granulite, quoted from 'Chemie der Erde' Vol.5.1930
- 11 Garnet amphibolite, quoted from Dengo (1950) p.876
- 12 Garnet amphibolite, quoted from Briere (1920) p.127
- 13 Eclogite, quoted from Davidson (1943) p.98,100
- 14 "
- 15 Amphibolized eclogite, quoted from Alderman (1936) p.508
- 16 Eclogite
- 17 "
- 18 Eclogite, quoted from Tilley (1937) p.560
- 19 Kyanite garnet amphibolite, quoted from Tilley (1937) p.560
- 20 Kyanite eclogite, quoted from Tilley (1937) p.430
- 21 Kyanite eclogite, quoted from Briere (1920) p.168
- 22 Eclogite, quoted from Briere (1920) p.168
- 23 Eclogite, quoted from Eskola (1921) p.36
- 24 Garnet pyroxene labradorite rock, quoted from Eskola (1921) p.92
- 25 Eclogite, quoted from Sahlstein (1935) p.11
- 26 Amphibole eclogite " p.13
- 27 " " p.14
- 28 Garnet gabbro, quoted from Gjelsvik (1947) p.11
- 29 Eclogite, quoted from Hezner (1903) p.466
- 30 Eclogite, quoted from Schuster (1878) p.368
- 31 Eclogite, average analysis from Williams (1932).343
- 32 Eclogite gabbro from Sittampundi complex
- 33 Garnetiferous hornblende diopside hypersthene rock, quoted from Rama Rao (1945) p.97
- 34 Plagioclase eclogite, quoted from Marchet (1925) p.244
- 35 Garnet amphibolite, " p.314
- 36 "
- 37 Eclogite, quoted from Switzer (1945) p.7
- 38-43 Eclogites, quoted from Briere (1920) p.168
- 44-48 Eclogites, quoted from Weiseneder (1934)
- 49-56 Eclogites, quoted from Niggli (1930) p.103,105,197,211
- 57-62 Garnet amphibolites " p.103,169,211,213
- 63 Garnet norite, quoted from Groves (1935)
- 64-68 Drusites (eclogites) quoted from Machkovtsev (1927)
- 69 Hornblende eclogite, quoted from Erdmannsdorfer (1938)
- 70-74 Hyperites, quoted from Brogger (1935) p.108
- 75-76 Hornblende hyperite, quoted from Brogger (1935) p.170

that the eclogites tended to fall in a definite zone and this has been shown as a probable eclogite field. The eclogite from Sittampundi complex is indicated by plot 32 in the diagram, while plot 33 and 63 are eclogitic rocks from the charnockite regions of Mysore and Uganda. All these three rocks are well within the eclogite boundary fixed by the writer. An inspection of the diagram will show that the tie lines of rocks 13, 15, and 25, representing paired analyses of eclogites and garnets in them, do not conform to those of the other eclogites. The line 13 represents an eclogite and the garnet from it described by Davidson (1943.) The composition of the garnet, which is almanditic, is also, in the opinion of the writer, indicative of the rock being a garnet amphibolite. It will be seen that the tie line 13 parallels the tie lines of garnet gabbros from the Adirondacks and Norway. The line 15 represents amphibolized eclogite and related garnet from Glenelg described by Alderman (1936). The analysis of the garnet used for the plot does not appear to be of high quality, but the line shown in the diagram follows the trend of the lines for gabbros. The line 25 represents an eclogite from Greenland and the related garnet described by Sahlstein (1935). The description of the rock suggested it to be garnetiferous amphibolite, and the trend of the tie line follows that of the gabbros. It will be noticed that points 13 and 15 for the rocks falls outside the eclogite field in the diagram. The data used in the diagram are shown in Table XXXIII.

It should be admitted here that in the absence of more data by way of paired analyses of garnet bearing basic rocks and their garnets, generalizations are unwarranted. At the same time, the diagram has helped in bringing out the general characteristics of the eclogites, as distinct from other garnet bearing basic rocks.

ORIGIN OF THE ECLOGITES

Two possible hypotheses can be offered to explain the origin of the eclogites: 1. Formation under metastable conditions from an original basic gabbro, with subsequent diaphoresis; 2. Formation under dynamothermal metamorphism at moderate depths in the presence of a catalyst, probably water.

Hypothesis 1

Riddle and Foster (1949) have suggested that kyanite, generally accepted to be a high pressure mineral, could be formed metastably, and the recent work of Bowen and Tuttle (1949) on the system $\text{MgO-SiO}_2\text{-H}_2\text{O}$, has demonstrated that anthophyllite can be formed metastably. Dengo (1950) has postulated that eclogites can be formed metastably, under conditions of regional dynamothermal metamorphism of intermediate grade. The formation of metastable facies is rather difficult to explain in the present state of our knowledge. Alderman (1936) thinks that the formation of omphacite is conditioned by the composition of the primary pyroxene and the availability of albite molecule, while Yoder (1950) has stated that the small amount of soda found in the eclogite pyroxene does not justify the assignment of special extreme conditions for its formation. Wieseneder (1934) has stated that the formation of eclogite may be a function of the bulk composition, a view which finds a parallel in the conclusion of Bowen and Tuttle (1949) who state in connection with the metastable formation of anthophyllite, that it may be a function of the total composition of the system $\text{MgO} - \text{SiO}_2 - \text{H}_2\text{O}$. It is postulated here that the formation of eclogite may be conditioned by the nature of the garnet formed,

which will determine the composition of the remaining minerals to be formed.

Backlund (1936) and Kranck (1935) have, on the basis of their study of the eclogites of Greenland, indicated the importance of shearing stress as an important factor in the formation of eclogites under conditions of extreme dynamic pressure.

It is thought that in the present instance eclogite was formed metastably during regional metamorphism from a basic gabbro. It is conceivable that pyropic garnet was formed by reaction between the olivine and a certain proportion of the anorthite molecule from the plagioclase. The plagioclase readjusts itself to a more sodic composition as proposed by Shand (1945) to which reference has been made before. This fits in with the observations made on an analyzed eclogite. The rock which has a normative feldspar with An_{79} indicates a modal feldspar An_{48} . Here it can be considered that 75% of the anorthite in the original plagioclase, combined with olivine, leaving behind a more sodic feldspar.

In the case of the bronzitic pyrope and bronzitic eclogite which have very little plagioclase, it is likely that the feldspar present originally may have been of very basic composition, and the small amount of soda molecule liberated during the formation of the garnet may have entered the clinopyroxene structure. The formation of the eclogite may be correlated with the first stage in the transformation of the anorthosites, during the migmatization and formation of Peninsular gneiss. It is suggested that the retrograde changes observable in the eclogitic were induced by lowering the pressure and elevation of the complex, at a later period followed by the intrusion of the younger granite.

Hypothesis 2 : An alternate suggestion for the formation of these eclogites would be that they were formed during the regional dynamothermal metamorphism during the Peninsular gneiss epoch with volatiles playing the role of catalyst. The process must have been rejuvenated during the intrusion of the younger granite, resulting in an assemblage showing retrograde as well as prograde characters. Further consideration of this hypothesis must await more critical field data.

METAMORPHISM OF THE COMPLEX AS A WHOLE

It is clear from the petrographic description of the rocks that we are dealing with rocks which have undergone profound mineralogical transformations, with little or no change in bulk chemistry. A comparison of the chemical composition of these rocks with others which have not undergone any metamorphic changes is possible from an inspection of Tables XXXI and XXXII. The only other instances of similar rocks are recorded from Messina country in Transvaal by Sohnge (1945) and Van Zyl (1950). Some of the corundum bearing edenite amphibolites from ^{North} Carolina described by Hadley (1949) bear a striking resemblance to the anorthosites of the Sittampundi complex. However, except for brief descriptions, no critical data are presented. Assuming that there has not been any appreciable change in the bulk composition of the various units of the complex, the following interpretation is possible:

Original Rock

Anorthosite

Gabbroic and Noritic
Anorthosite

Present Rock

Leucocratic anorthite
gneiss and related clinozoisite, garnet assemblages.

Bytownite and anorthite
edenite gneisses, anorthite
anthophyllite edenite rock, etc.

<u>Original Rock</u>	<u>Present Rock</u>
Troctolite	Edenite gneisses and segregations
Basic gabbro	Bronzitic pyropite
Gabbro	Eclogite series
Chromitite	Pargasite chromite rock
Bronzite	Perknites, essentially pargasite and anthophyllite.

The above correlation is offered purely on the basis of the similarity of the chemical compositions and no petrographic evidence has yet been found to confirm the above suggestion.

Hadley (1949) has presented petrographic evidence to support his suggestion that the edenite amphibolites have been derived from troctolites. He writes:

In many of the specimens studied, coronoid texture characteristic of the troctolite is more or less well preserved in the amphibolite. It is most evident in aggregates of clear, fine-grained amphibole, or of amphibole and spinel, surrounding plagioclase grains or masses of recrystallized enstatite. In the coarser grained amphibolite, however enstatite and all traces of coronoid texture are absent, and chromite and corundum are almost universal accessories. The edenite-amphibolite thus appears to have resulted from an alteration of troctolite amphibolite, in which the fine grained enstatite and amphibole of the coronas has been changed to coarser-grained edenite with little change in the feldspar. The two rocks grade into each other by various degrees of change in texture and mineral content and are commonly very hard to distinguish in the field.

It is conceivable that these relict structures were obliterated during the second stage in the transformation of these rocks. The metamorphic history of these rocks can be summarized as below:

Stage 1. Regional metamorphism and migmatization. Original rocks of anorthositic facies transformed to anorthite

amphibole assemblages, by recrystallization. Gabbroic rocks metastably form eclogite rocks. Chromitites are amphibolized and recrystallized with elimination of TiO_2 from chromite frame work.

Stage 2. Dynamothermal metamorphism associated with the intrusion of younger granite; rich in mineralizers. Anorthositic rocks undergo further transformation, with resultant formation of clinozoisite, corundum and garnet. Eclogitic rocks develop retrograde characters due to the action of mineralizers at elevated temperatures. Talcose minerals form in the chromitites at the expense of amphibole.

ORIGIN OF CHROMITE

As mentioned previously, the anorthosites carry conformable seams of chromite extending for several miles along the strike, varying in thickness from a few inches to ten feet and more. These chromitites are significant in that they unequivocally prove the igneous origin of the complex as a whole.

The origin of chromite has been discussed at some length by Sampson, Ross, Singewald, Fisher, Keep and others, and in relation to the problem of the chromites of this complex, Sampson's (1932) discussion of the south African deposits is significant. It has been stated earlier in this paper that the chromitite anorthosite relationship in our complex bears a striking resemblance to the Dwars River section of the Bushveld complex. The mineralogy of the chromitite and related host rock in the Dwars River sequence and in the Sittampundi complex are shown below:

Dwars River

Chromitite composed of poikilitic plagioclase or bronzite or both with scattered chromite crystals. Biotite present occasionally.

Anorthositic Norite

An₆₇

Sittampundi

Chromitite composed of poikilitic pargasite or anthophyllite or both with scattered chromite grains, corundum present at contact with anorthosite

Anorthite or bytownite edenite gneiss.

An₈₀₋₁₀₀.

It may be seen from the above comparison that the Sittampundi sequence merely represents a metamorphic equivalent of the Dwars River rocks. Sampson has interpreted the Dwars River sills as fillings of residual chromite magma in cracks developed in the crystallized anorthosite. While this may be a reasonable assumption for sills of limited lateral extent, it is not applicable in the present instance, where individual chromitite bands can be traced for over ten miles, and also in view of the fact that the small scale bands of chromitite in hand specimens do not show knife edge contacts. It appears reasonable to assume that the chromite bands have been formed during the course of crystallization of the magma, with settling of chromite at different levels, which may be attributed to local disturbances in the magma chamber. Hess (1938) is inclined to favor such an interpretation, and his theory for the origin of mafic bands in anorthositic rocks may equally well apply in the case of small scale chromitite bands in anorthosite.

Bateman (1951) has proposed a theory of 'late gravitative liquid accumulation', to account for the presence of oxide ore bodies in basic rocks. He envisages the enrichment of residual magma in metallic oxides, which accumulates on a floor of early crystallized silicates. He believes that under quiescent conditions this would form a stratiform deposit, and under pressure result in late magmatic injections. This theory does not offer a satisfactory explanation for the formation of bands of chromitite in anorthosite.

It has not been possible to interpret the origin of the chromite, from thin sections and polished sections as all primary evidence has been

obliterated by metamorphism. It appears that field evidence indicates that chromite crystallized normally, as regular bands towards the bottom of the sheet. The absence of transgressive relationship as also the absence of xenolithic anorthosite within the several chromitite horizons examined in the field show that the chromitite in this case is not late magmatic.

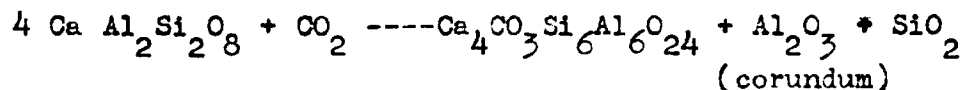
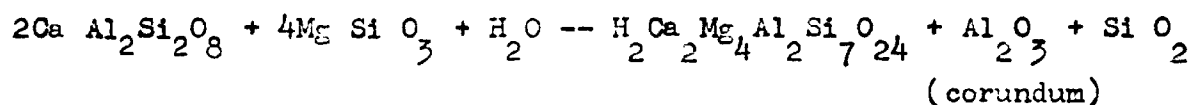
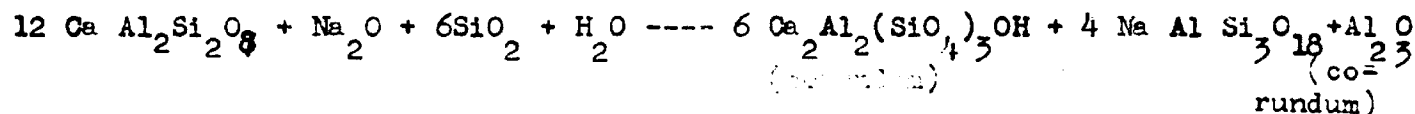
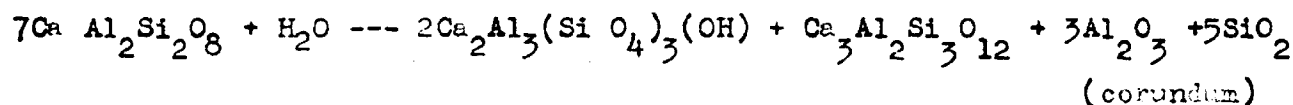
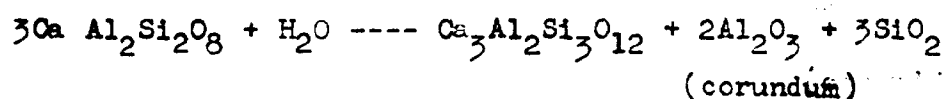
ORIGIN OF CORUNDUM

The anorthositic rocks of the complex which are extremely aluminous in bulk composition contain corundum in varying amounts. The more mafic anorthosites do not carry much corundum, but the felsic varieties composed of anorthite invariably contain 2-3% corundum scattered as small basal plates and large porphyroblastic hexagonal crystals. The corundum crystals vary in diameter from 2 mm. to as much as 10 cm. A pinkish variety of corundum is found in the pargasite-chromitite layers, generally as granular crystals.

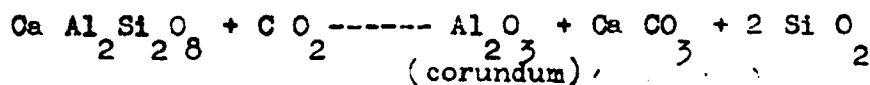
Hadley (1949) discussing the origin of corundum found in the edenite amphibolites of North Carolina, writes:

The disseminated corundum in the edenite-amphibolite appears to have resulted from concentration of alumina originally contained in the plagioclase of the troctolite. The first step in this process was the development of the coronas along the boundaries between grains of plagioclase and olivine in the troctolite. In this stage an intergrowth of spinel and amphibole apparently replaced part of the plagioclase, producing a relative concentration of alumina in the mineral spinel ($\text{MgO} \cdot \text{Al}_2\text{O}_3$). In the second stage, the spinel was destroyed as additional amphibole (edenite) was formed, and the excess alumina from the spinel was deposited as corundum. Much of this corundum was deposited around or replaced disseminated grains of magnesia-rich aluminian chromite originally present in the troctolite, thus accounting for the common association of corundum and chromite in the edenite amphibolite. Some of the alumina, however, wandered out into local fractures in the amphibolite and was deposited as larger crystals in the cross cutting veins.

While direct microscopic evidence for the above mode of formation of corundum is lacking the occurrences of spinel-pargasite-corundum paragenesis in some of the rocks developed in the contacts between anorthosite and chromitite is indicative of such a reaction. In Chapter III several possible reactions have been shown to explain clinozoisite, anorthite, garnet paragenesis, with consequent liberation of corundum. Some of these reactions are indicated below:



The frequent presence of calcite rims around corundum indicates the following reaction:



Kolderup (1940) has described corundum anorthosite facies from the Bergen Arc of Norway which lends support to the suggestion made here of considering the original magma being rich in alumina. Van Zyl (1950) refers to the presence of a corundiferous zone in the anorthosite gneisses of Soutpansberg without any petrographic details, but presumably the occurrence is similar to that in the Sittampundi rocks.

ORIGIN OF BANDING IN THE COMPLEX

The mode of occurrence and the layered character of the complex as a whole suggests that some type of primary banding was present during the cooling and crystallization of the magma. Cooper (1936), Coats (1936), Hess (1938), Van Zyl (1950) and Turner (1951) have discussed the problem in some detail. Cooper invokes reinjection of magma to explain large scale banding, but considers small scale rhythmic layering to be due to change in physical conditions in the magma chamber. Coats, on the basis of laboratory experiments, concluded that rhythmic layering was caused by the differential settling of crystalline constituents within the bands. Hess has offered a clear explanation for the origin of small scale and large scale banding in ultramafic complexes. He believes that banding has been induced by (1) the relative differences in density between each of the two main constituents settling, plagioclase and pyroxene, compared to the density of the magma; (2) disturbance of the normal state of quiescence in the magma by short epochs of mild, but irregular, turbulence.

Van Zyl considers the banded structure of the northern Transvaal anorthosites to be formed by rhythmic differentiation by a process of gravitational settling. In explaining the origin of layering, he writes:

It may be visualized that the first formed femic minerals, being of higher density than a melt from which the femic and salic constituents may crystallize, would tend to sink. Similarly salic minerals being probably lighter than a melt from which both femic and salic minerals can crystallize, would tend to rise. The two types of crystals would cross each other in their movement. In the initial stages of crystallization, when there are still relatively few solid constituents, in the essentially fluid magma, the crystals would not mutually interfere with each other and the tendency would be separation of the magma into a basal layer of predominantly femic

constituents and an upper layer of mainly salic minerals.

If however, the magma is relatively viscous, the crystals numerous and the rate of movement slow, it may be visualized that the crystals would mutually interfere with each other in the process of moving up and down respectively. In this manner certain planes of relative stagnancy may arise through mutual interference, forming a network of crystals, partly impenetrable to crystals moving vertically. At this stage there is a very delicate balance which may be easily disturbed by magma flow. However, salic constituents continuing to accumulate from below and femics being continuously added from above would serve to stabilize such a zone of relative impermeability. Then between any two such stabilized zones, the process may be repeated, and as soon as a band of light and dark constituents has been there established, it may be repeated yet again, on a smaller scale between this and the next band. Probably the position between the two established bands, where the next one is most likely to form, is determined by the relative rates of up and downward movement of the two crystal types respectively.

By this process can be explained (i) the separation of a magma into a relatively basic lower portion and a salic or more acid upper portion (ii) the banded structure; (iii) the occurrence of banding on a regional scale and intermediate banding on a smaller or even hand specimen scale. A thick sheet may thus be separated into distinct layers in each of which differentiation may then continue independent of the next layer, and the resultant interruption of progressive changes from the top to the bottom of the formation as a whole need therefore not be interpreted as separately intruded sheets representing pulsations from a common magma.

The formation of small scale banding in a crystallizing magma and its absence in another must be due to several factors which collectively create or destroy the delicate equilibrium necessary to establish the initial zone of relative impermeability. Likely factors are the viscosity of the magma, the rate of cooling, the thickness of the sheet, the extent of magma flow during cooling, the size of the crystals formed, the specific gravities of the crystals and their rates of movement in a magma.

It may be seen that the above concept is merely an expanded version of the first hypothesis of Hess. Turner and Verhoogen (1951) postulate the slow cooling and continued emplacement of a magma sheet fed from

several sources, with subsequent activity of convection currents, and more local intermittent turbulence, to explain rhythmic layering in stratiform lopoliths.

In the present instance, on the assumption that some of the layering was primary, the explanation offered by Hess appears most apt. As has been suggested previously, the chromitite bands may have also been formed by a similar process.

It should, however, be borne in mind that we are dealing with a body which has undergone metamorphic transformations, and it would not be unreasonable to suggest that banding may also have been induced by metamorphic differentiation.

PREFERRED ORIENTATION OF MINERALS

The preferred dimensional orientation of amphiboles and clinozoisite has been referred to earlier, as also the platy parallelism of the calcic plagioclase. It is conceivable that the rocks had a primary preferred orientation of certain minerals which was accentuated during recrystallization. Hall (1932) has recorded preferred orientation in some of the Bushveld rocks, and Peoples (1936) in the rocks of the Stillwater complex. the marked horizontal lineation can be attributed to stress during the tilting of the sheet. This would explain the linear parallelism of clinozoisite and edenite in the anorthosites and pargasite in the chromitites. The fact that the adjacent amphibolites have a conformable linear structure is in support of this view.

In contrast to the amphiboles, the corundum porphyroblasts lie in the foliation with their longer axis perpendicular to the lineation. It is

thought that the alumina liberated must have moved along the planes of foliation, and crystallized out with their long axis in the direction of least pressure. This would also explain the tendency of amphibole crystals in the rock to wrap around the corundum porphyroblasts, indicating that corundum forced itself out pushing around the plagioclase and hornblendes.

CHAPTER VI

PETROGENESIS AND SUMMARY

The rocks of this complex are unique in many respects, and the only other occurrences of similar rocks have been recorded from the Messina country of northern Transvaal in South Africa, described by Sohnge (1945) and Van Zyl (1950). Some of the edenite amphibolites described from Carolina by Hadley (1949) are similar to the anorthositic rocks of the Sittampundi complex. These occurrences have been considered igneous in origin, and the African occurrences have been interpreted to be formed by gravity stratification during differentiation of a basic magma.

During the last two decades, several gravity stratified sheets have been described from different parts of the world by Hall (1932), Buddington (1936), Peoples (1936), Cooper (1936), Stewart (1946) and others. In Table XXXIV the vertical sequence in the Sittampundi complex has been tabulated together with those of the Bushveld and Bay of Island complexes. While it is realized that too close an analogy cannot be drawn, the comparison does indicate that the Sittampundi complex is probably also of the gravity stratified type. It is difficult to interpret the sequence of crystallization as all the primary minerals have been transformed, but on the basis of bulk chemistry, the exposed section of the Sittampundi complex corresponds to the Transition zone of the Bushveld and the lower zone of the Bay of Island complexes.

The following are some of the salient points which unequivocally point to an igneous origin of these enigmatic rocks:

1. The whole complex shows a striking resemblance to classical occurrences of gravity stratified sheets. The bulk chemistry of the various rocks of the complex bear a striking similarity to rocks from stratiform sheets.

TABLE XXXIV PAGE 150

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Material has been photographed as
received from Princeton University
Library.

UNIVERSITY MICROFILMS

Table XXXIV

COMPARATIVE VERTICAL SEQUENCE IN SOME GRAVITY STRATIFIED SHEET COMPLEXES

Name	Bushveld	Bay of Island	Sittampundi
Length	200 miles	65 miles	25 miles
Width	150 miles	10 miles	15 miles
Thickness	2 to 3½ miles	7 miles	7000 feet
Age	Pre-Cambrian	Ordovician	Pre-Cambrian
	Acid rocks (granite, granophyre & felsite)	Roof volcanics	Top eroded
Upper zone	Gabbro in part with interstitial granophyre Andesine anorthosite, diallagite etc. Feldspar An ₄₅₋₆₀ Nerite, Labradorite anorthosite, hypersthene diallagite, diallage hypersthene etc. with	Gabbro in part banded with some zones of troctolite olivine gabbro feldspathic dunite etc. with only a little pyroxenite.	Eclogite gabbro Feldspar An ₄₅₋₆₀ orthopyroxene En ₈₄ garnet Mg ₄₅₋₅₀
Main zone	with several chromite layers and a platinum horizon. Feldspar An ₇₀₋₈₀	Dunite, peridotite, subordinate pyroxenite, gabbroic anorthosite. Several chromite layers.	Also several thin layers of eclogite, garnet pyroxenite and bronzitic pyroxite. Orthopyroxene En ₈₅ Garnet Mg ₅₀₋₅₅
Transition zone	Basic norite, bronzitite, bytownite anorthosite, minor chromite layers, local sulphide lenses.	Basal group?	Basal group hidden(?)
Chill zone	(Basic norite, bronzitite (bytownite anorthosite (Feldspar An ₇₃ (Hypersthene An ₅₈		
Mineralogical variation	Feldspar increasing in anorthite content downwards. Pyroxene magnesian towards base	Bytownite to labradorite. Olivine Fa to Fa ₂₀ . Orthopyroxenes at the base and clinopyroxenes at top.	Feldspar An ₄₅₋₁₀₀ Orthopyroxene En ₈₀₋₈₆ Garnet Mg ₄₅₋₆₀
Segregations & dikes	--	Pyroxenite veins, gabbro pegmatite, feldspathic dunite basalt porphyry, gabbro, granite	websterite pegmatite
Satellite intrusions	Norite, quartz dolerite locally pyroxenite, olivine bronzitite etc.	Ultramafic rocks, gabbro and hornblende gabbro.	Pyroxenite websterite

2. The presence of several seams of chromitite within the anorthosites of the complex, proves conclusively their genetic relationship. The composition of the chromite is similar to the composition of chromites from other gravity stratified sheets.

3. The eclogites carry garnets free from inclusions, which Eskola has considered a good criterion for garnets of eclogites derived from igneous rocks.

4. The presence of cordierite corundum rock, interpreted as an inclusion in the anorthosite, points to an igneous origin of the anorthosites and related rocks.

5. A statistical analysis of the twinning laws of the plagioclase feldspars of these rocks indicate a fair proportion of complex twin laws. This feature has been considered by Turner as evidence indicating an igneous parentage. The complex twins of plagioclase may be relicts preserved by partial recrystallization of the rocks. The skeletal diopside crystals seen in some rocks is in support of the interpretation that relict features have been preserved in these rocks.

6. The absence or presence in very minor amounts of TiO_2 , P_2O_5 , MnO and SrO is rather characteristic of rocks from differentiated sheets, and the Sittampundi rocks show this feature.

In assuming an igneous origin for these rocks, as a working hypothesis, the possibility of their being metamorphic derivatives from limestones of peculiar composition, has not been lost sight of. However the evidence in favor of such a hypothesis is mostly negative, as may be seen from the following points.

1. It would be difficult to get a section of impure limestone with gradational compositional range, to give rise to rocks of varied composition like anorthosite and eclogite.

2. While it is possible that small bodies of para-anorthosite may be formed by metasomatism of limestone, it is difficult to visualize an extensive belt of anorthosite formed by such a process.

3. The homogeneous distribution of corundum in the anorthosite does not indicate their origin from a bauxitic layer in the sedimentary limestone.

4. The chromitite is beyond doubt igneous, and the mineralogy is not indicative of a placer in limestone.

5. In the region around the complex there are several bands of crystalline limestone and marble, but none within the complex itself.

It may be seen from the above that present evidence is in favor of an igneous origin of these rocks.

SUMMARY

Mineralogy

1. The garnets from the eclogitic rocks are pyropic and support the view that these rocks are eclogites.

2. The garnet from the anorthosite has a peculiar composition with high grossularite molecule and fair amount of pyralmandite molecule. According to Ramberg this is indicative of high pressure formation.

3. The plagioclase feldspars of the anorthositic rocks have an unique compositional range of An_{80} to An_{100} . Anorthites with An_{98} and An_{99} have been found in these rocks, and probably represent the nearest approach in nature to synthetic anorthite. Statistical analysis of the laws of twinning of these plagioclases indicate a fair proportion of twins characteristic of magmatic rocks. It has been found also that the refractive indices of calcic feldspars are very critical for fixing their composition. Other methods are found to have an accuracy of only $\pm 5\%$ An .

4. The monoclinic amphiboles from the anorthosite and chromitite were chemically analyzed and their composition correlated with the determined optical properties. The amphibole in anorthosite is edenite, and that in chromitite, pargasite. It is thought that they represent a sub-series in the hornblende series.

5. The anthophyllite in the anorthosite has been found to be rich in alumina, and hence a gedrite, or, according to Rabbitt, an aluminian anthophyllite. The value N_z for this and other aluminian anthophyllites fall above the curve of Rabbitt. The anthophyllites in the chromitites were found to have lower values of N_z . It is conceivable that in these rocks the anthophyllites may vary from magnesian to aluminian types.

6. The cordierite from the rock interpreted as in inclusion is of a magnesian variety and optically negative. A review of the literature has shown that the present interpretations for the anomalous optical character of some cordierites are unsatisfactory.

7. The clinozoisite in the anorthosites is low in epidote molecule, though compositional variations are noticeable within a single thin section.

8. The chromite from the chromitite is rich in the spinel molecule falling at the boundary of chromian spinel and aluminian chromite.

9. The corundum is interpreted as derived from the original rock during the formation of amphibole and later during the formation of garnet and the epidote minerals.

10. It is postulated that the mineral transformations took place during two periods of Archaean metamorphism.

Petrology

1. By analogy with gravity stratified sheets this complex is interpreted as a stratiform sheet.

2. The bulk chemistry of the rocks is in fair agreement with those from other described occurrences.

Some of the layering is considered primary, and it is suggested that the chromitite horizons were formed during the normal fractional crystallization of a basic magma under quiescent conditions, with recurring turbulence or pulsation of the magma within the chamber.

4. The eclogite series are interpreted as original gabbros of the complex. It is suggested that they were transformed to eclogites metastably during the first period of regional metamorphism. A triangular diagram representing the percentages of (FeO + MnO), MgO, and CaO has been constructed and the analyses of 76 garnet bearing rocks

and the garnets in some of them plotted therein. The tie lines drawn for the paired analyses indicated differing trends for the eclogites and gabbroic rocks. An eclogite field has been demarcated in the triangular diagram.

5. The anorthositic rocks fall in the amphibolite facies, though they tend to fall in generally restricted fields of the A C F diagram for the cordierite anthophyllite sub-facies. The analyzed eclogite and related garnets fall in their appropriate fields in the A C F diagram of Eskola for the eclogite facies.

6. The following sequence of events are envisaged:

- i. Emplacement of basic magma in Dharwar sediments during a period of quiescence. Fractional crystallization and gravitative differentiation took place with formation of a layered complex.
- ii. Metamorphism and regional migmatization resulting in the formation of the Peninsular gneiss induced chemical and mineralogical transformations in the rocks of the complex.
- iii. Elevation of the complex to the level of erosion with accompanying retrograde changes of eclogites. Top of complex eroded.
- iv. Forceful intrusion of younger granite domed up the complex, which stands on its edge dipping steeply away from the center of intrusion. Considerable mineralogical changes in the anorthosites, induced by mineralizers from the granite. Consequent formation of epidote minerals, garnet, and corundum. The eclogites develop retrograde characters.

7. The name Sittampundi Complex is proposed for this body of basic rocks.

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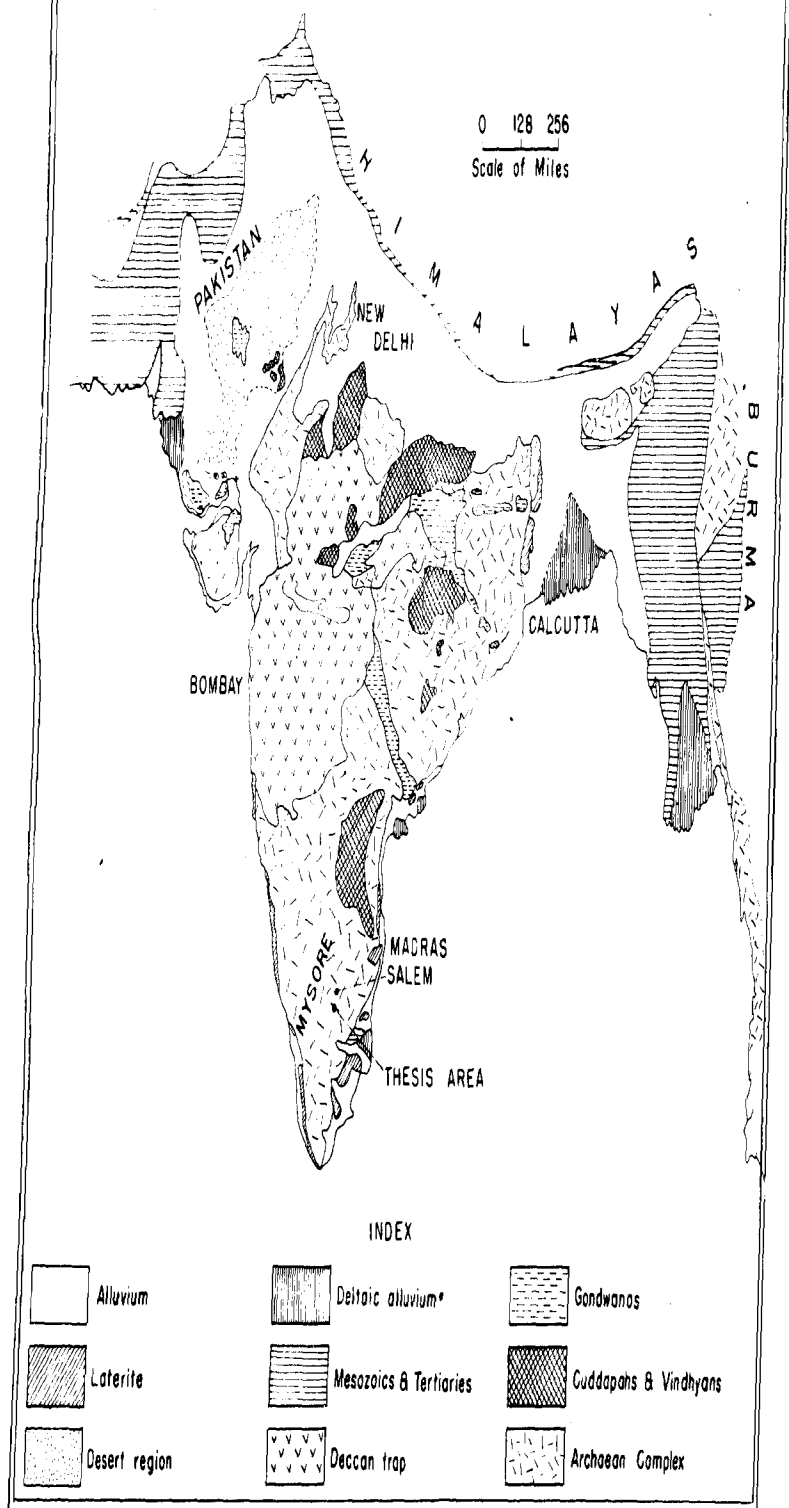
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GEOLOGICAL SKETCH MAP OF INDIA

PETROLOGICAL MAP OF THE SITTAMPUNDI ANORTHOSITE GABBRO COMPLEX SALEM DISTRICT, MADRAS, INDIA.

EXPLANATION



P
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	Peninsular gneiss and younger granite	GNEISS
	Pyroxenite (Websterite)	CHALCOPHYRE
	ECLOGITE GABBRO SERIES	SITTAMPUNDI
	Pyroxene garnet rock, Hornblende plagioclase garnet rock, etc.	
	ANORTHOSITE SERIES	SITTAMPUNDI
	Perkinite and Chromitite bands, Anorthite hornblende gneiss, Anorthite clinzoisite cerundum rock, Bytownite anthophyllite rock, Gorundum cordierite anthophyllite rock, etc. Chromitite bands shown by heavy lines	
	Peridotite	DHAU
	Amphibolite	
	Magnetite quartzite	
	Calciophyre & crystalline limestone	

Contact, dashed where approximately located

Strike and dip of foliation

Horizontal lineation

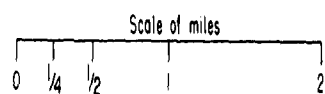
Railway line

Country road

District highway

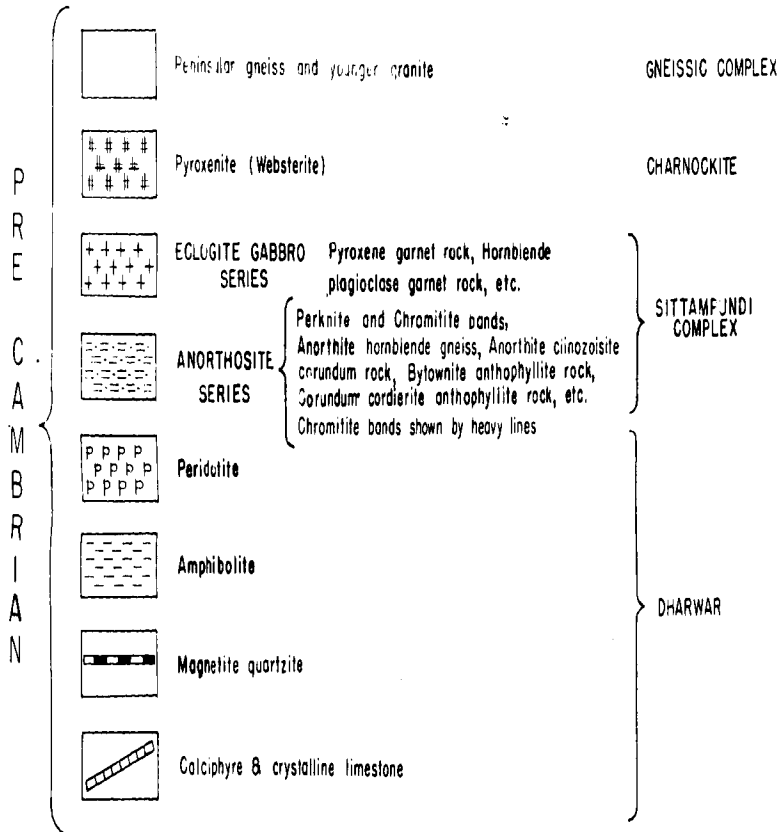
Height above mean sea level 702

N



PETROLOGICAL MAP OF THE SITTAMPUNDI ANORTHOSITE GABBRO COMPLEX SALEM DISTRICT, MADRAS, INDIA.

EXPLANATION



Contact, dashed where approximately located

Strike and dip of foliation

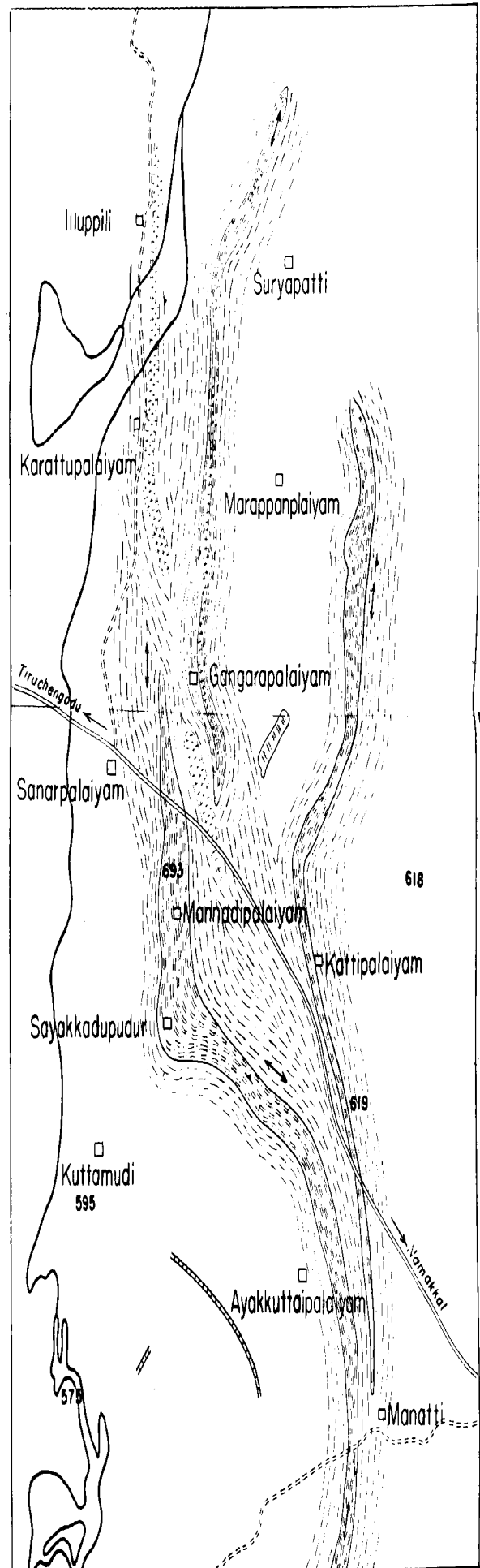
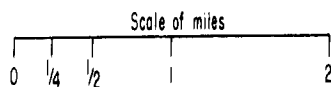
Horizontal lineation

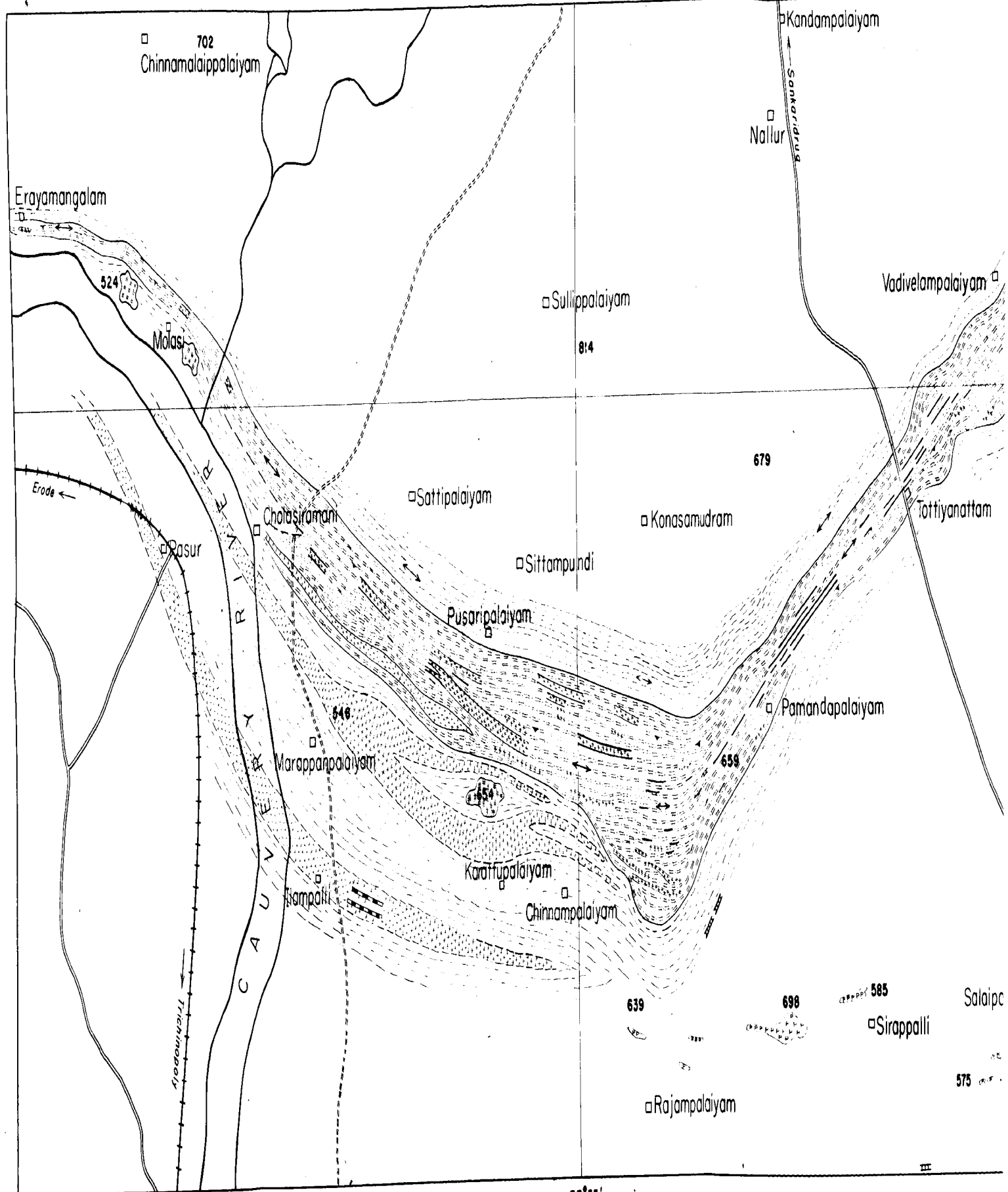
Railway line

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District highway

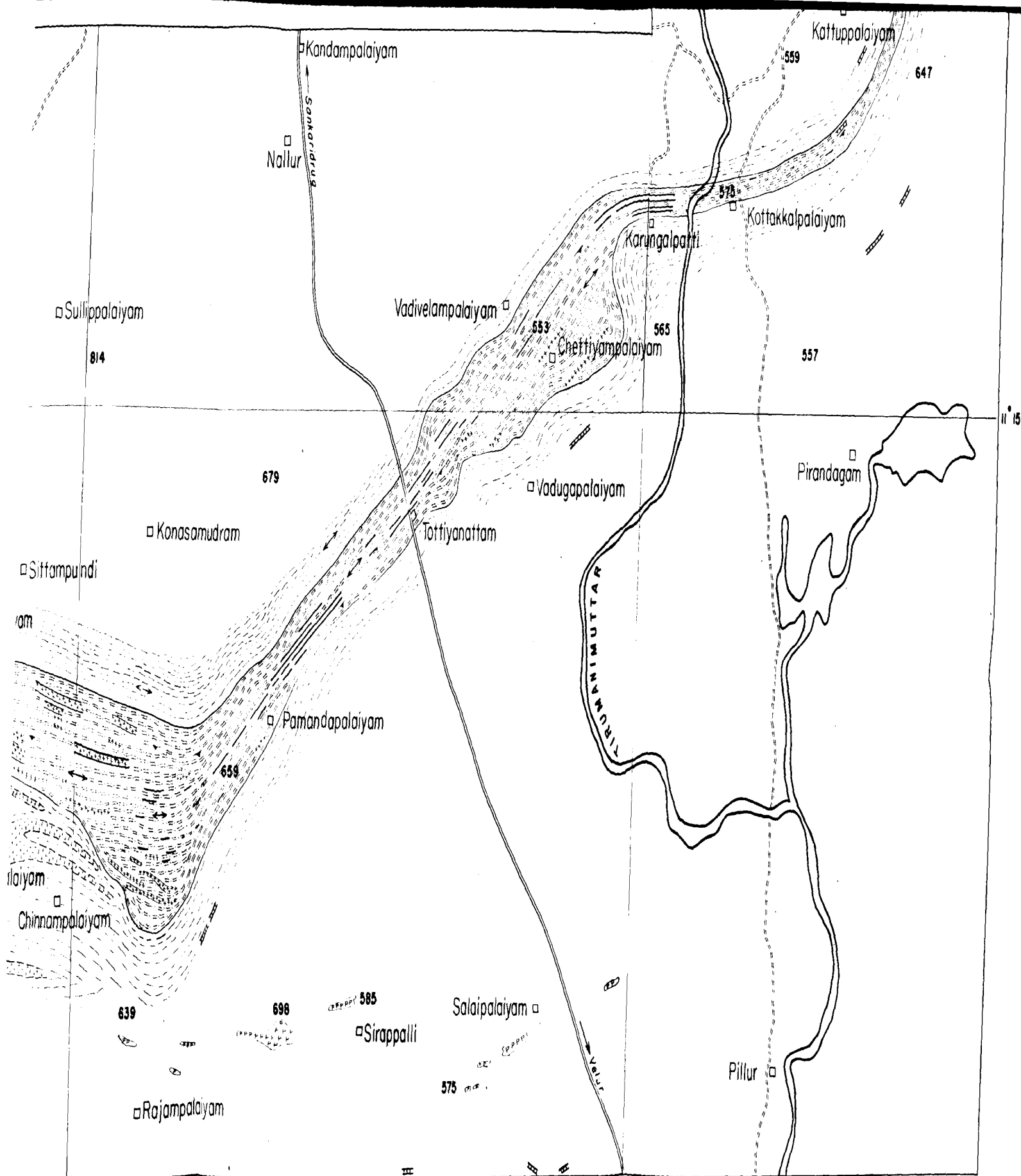
Height above mean sea level 702





77° 50'

77° 55'



77° 55'

78° 0'

11° 15'