Adela Aguilar M.

Ash-Flow Tuffs: Their Origin, Geologic Relations and Identification *and* Zones and Zonal Variations in Welded Ash Flows

with Foreword by
ROBERT L. SMITH

Reprinted from U.S. Geological Survey
Professional Papers 354-F and 366

Managing Editor
JONATHAN F. CALLENDER

NEW MEXICO GEOLOGICAL SOCIETY
SPECIAL PUBLICATION NO. 9
1980

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FOREWORD

by

Robert L. Smith

Twenty years have passed since publication of U.S. Geological Survey Professional Papers 366, *Ash-flow tuffs: Their origin, geologic relations and identification,* by C. S. Ross and R. L. Smith (1961), and 354-F, *Zones and zonal variations in ash-flows*, by R. L. Smith (1960). As these papers are now being republished, perhaps a few words are appropriate to clarify their historical evolution and to view them in the context of the present time.

Clarence Ross and I began an intensive general study of microscopic and field characteristics of "welded tuffs" in 1948, in the hope that such a study would aid our interpretation of the Bandelier Tuff, Jemez Mountains, New Mexico. The study led to a general overview which became Professional Paper 366. Professional Paper 366 was written during the late 1940's and early 1950's. The paper was virtually complete in its present form in 1954 and should have been published in 1955 or 1956. For various reasons the paper with but minor updates to about 1956, did not go to press until 1960, and we feared that it would be obsolete before it was published. Moreover, the first printing of PP366 in 1960 was contracted out by the Government Printing Office and the reproduction of the plates was unacceptable and reprinting was required. This reprinting by GPO delayed the publication date until 1961 *after* the publication of PP 354-F and my review paper "Ash Flows" (1960). For the specialist in welded tuffs Professional Paper 366 probably was obsolete when published, but fortunately specialists were few and the paper has long been popular and useful to students, teachers and to geologists not specialized in the geology of silicic volcanic rocks. Professional Paper 354-F was conceived during the mid-1950's, written in 1958, and published in June of 1960, the same month that "Ash Flows" appeared in the Geological Society of America Bulletin. This latter paper was written in 1959 and, although it was labeled a review paper, it actually represented a five-year conceptual advance beyond Professional Paper 366, and contained much additional data. However, the main value of Professional Paper 366 is in the many photomicrographs depicting variations in ash-flow tuffs, and in the historical summary that attempts to outline the evolution of thought leading to modern concepts. These sections are probably of most value to students and have not yet been superseded.

Professional Paper 354-F introduces the concept of the "cooling unit" and provides some genetic and descriptive order to the many lithological variations found in welded tuffs. The cooling unit was conceived by the author as a device to provide genetic meaning to map units, as well as an aid to mapping, and had its origin in the very complex units of the Bandelier Tuff. The fact that no Bandelier-type units are depicted in Professional Paper 354-F, has puzzled several observant students of these rocks, and on several occasions I have been asked "why?"

Professional Paper 354-F deals primarily with zonal variations in what I termed "simple cooling units" and although concepts of more complex units were introduced they were not illustrated. The more complex units were to have been the subjects of a sequel to the paper. Illustrations, an oral presentation and an abstract were prepared for an International Association of Volcanology and Chemistry of the Earth's Interior symposium in 1962 in Italy, but alas! the paper was never written.

The cooling-unit concept was built around the premise that the two major variables controlling the lithologic variations in welded tuffs are emplacement temperature of the ash flows and the thickness of the resulting deposit. As originally planned, Professional Paper 354-F was to have been written around a thickness-temperature hierarchy of examples of actual cooling units, but this proved to be impractical at the time. Instead, the model was developed from the then existing fragments of cooling units whose properties could be reasonably extrapolated from one deposit to another.

The sources for the illustrations in plate 20 of the original PP354-F may now be of historical interest. Figure A was patterned after the Battleship Rock Tuff, Jemez Mountains, New Mexico; figure B was patterned after the Walcott Tuff of Idaho; figures C and D are hypothetical composites based on observations of a large number of vertical sections of devitrified units seen over a period of years in the western United States. A detailed listing of these units, even if they could all be recalled, is impractical here, but the welded tuffs of the San Juan Mountains, Yellowstone, and southeastern Utah, certainly played a dominant role.

Once these "simple" patterns of plate 20 were rationalized in a temperature-thickness context, the "compound" nature of the Bandelier Tuff units could then be recognized and understood in terms of a cumulative series of ash flows of systematically increasing emplacement temperatures and, ultimately, of changing compositions. Much of this reminiscence now seems trivial but in the 1940's and 1950's there were major problems. For years we were puzzled as to why "vitrophyre zones," so common under many welded tuff sheets, are absent in the Bandelier Tuff outside the caldera, but present inside. This can now be explained by the compound nature of the Bandelier cooling units. Such an explanation gives insight into eruption mechanics.

The "zone of granophyric crystallization" was postulated on the basis of observations made on a very thick cooling unit in the Chiricahua Mountains, Arizona (Member 6 of Enlows, 1955) and on the Superior Dacite (now Apache Leap Tuff of Peterson, 1969), Arizona. The "zone of fumarolic alteration" was largely speculative and, although eroded off in most tuffs, probably exists only as a discontinuous zone in most tuff sheets. In 1975 I encountered for the first time a continuous "zone of fumarolic alteration" on the ash flows surrounding Okmok caldera on Umnak Island, Aleutian Islands, Alaska. This zone was nearly everywhere present and ranged in thickness from about 0.1 to about 3 meters.

Professional Papers 366 and 354-F should be updated, amplified and recast into a simple quantitative synthesis of those rocks that we know as ash-flow tuffs. I have toyed with the idea for some years, but to date have only outlined the problem. The c
tion of such a complex task would be professi
rewarding and of interest to advanced studen
would destroy the simplicity that makes thes
lications useful to beginning students.

Modern studies of ash-flow tuffs are bec
strongly focused in two directions: 1) Mather
modeling of eruption mechanics and 2) quant
evaluation of chemical and mineralogical evol
Of the two main areas of study, I think that er
mechanics is fascinating and particularly signifi
extended to problems of magma generation, r
rise in the crust, and plate tectonics. However,
think that studies that relate to the chemical
tion of magmas, volcano periodicity and pred
crustal evolution, ore deposits and their reserve
certain energy resources will form a major w
future research in earth science. Riding the c
the wave will be in-depth studies of pyroclastic
particularly ash-flow tuffs. We have only just
to tap the real wealth of knowledge stored in
rocks.

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PREFACE

Both of these papers have been out-of-print for a number of years, much to the dismay of an ever-growing number of geologists who by choice or necessity find themselves working with volcanic rocks. Because much of the pioneering work on ash-flow tuffs described in both papers was done in New Mexico and because New Mexico, as well as the rest of the southwestern United States and northern Mexico, contains widespread accumulations of ash-flow tuffs that are currently under intensive study, the New Mexico Geological Society felt it was both appropriate and timely to re-issue these two classic contributions to modern volcanology. The actual reprinting effort would not have been realized, however, without the enthusiastic support and full cooperation of the U.S. Geological Survey's Office of Scientific Publications which supplied all of the original photographic plates.

Just to keep the record straight, the original inspiration to reprint the two papers also stems, in no small part, from a long, frustrating and ultimately unsuccessful search for an original copy of Professional Paper 366 for my own library.

James M. Robertson, Past President,
New Mexico Geological Society

Ash-Flow Tuffs: Their Origin Geologic Relations and Identification

By CLARENCE S. ROSS *and* ROBERT L. SMITH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 366

A study of the emplacement, by flowage, of hot gas-emitting volcanic ash; its induration by welding and crystallization, and criteria for recognizing the resulting rock

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1961

UNITED STATES DEPARTMENT OF THE INTERIOR
FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY
Thomas B. Nolan, *Director*

First printing 1961
Second printing 1964
Third printing 1968

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ASH-FLOW TUFFS: THEIR ORIGIN, GEOLOGIC RELATIONS, AND IDENTIFICATION

By CLARENCE S. ROSS and ROBERT L. SMITH

ABSTRACT

Pyroclastic materials, which are interpreted as having been deposited by flowage as a suspension of ash in volcanic gas, are becoming widely recognized as major geologic episodes. These may be unconsolidated, indurated by partial welding, or welded into a compact rock. Many students are working on these materials and the interest in them is so widespread that need for a coordinated treatise on them has developed. This report deals with the history of the concept of their origin; gives detailed descriptions of their character and mode of occurrence; gives criteria for their recognition; and considers their distribution and consolidation.

The terminology to describe ash flows and the reasons for avoiding the invention of new specific names, or the redefining of old ones, are stated. The terms used are given and defined, so far as possible, by quotations from authoritative sources. The use of descriptive phrases, where generally accepted specific names are unavailable, is the usage adopted.

The evolution of geologic concepts which led eventually to an understanding of the distribution and, in some deposits, the welding of tuffs is traced. Prior to about 1900, geologists argued as to whether these materials represented peculiar volcanic lava flows, or were pyroclastic in origin. The development of a better understanding is traced through the discussion of geologists who reported on the great eruptions of Pelée, Soufrière, and the Valley of Ten Thousand Smokes, and by other geologists who studied analogous ancient eruptions.

Recognition of ash-flow materials involves both field observations and laboratory studies. These are presented in some detail, and lead to the conclusion that the ash-flow materials may be recognized by either of these approaches, but for some occurrences both are required. The field relations that are presented for evaluation are: extent, thickness, the relation of overload to welding, jointing, erosional forms, inclusions of alien materials or pumice fragments, devitrification, and the relations to source centers. Experience with distinctive features commonly allows identification of ash-flow deposits even at a distance of many miles.

Laboratory studies that require description and evaluation include chemical analyses, the relation of composition to other features, porosity and its relation to overload and welding, and the temperature of welding. Microscopic studies reveal a large number of variables that demand consideration and discussion of their relative value in identification. These include a variety of primary glassy shard structures, the greatly varied modification of the shards by compression, welding, and devitrification. These factors may leave clearly significant evidence of origin, or this may be obscured in varying degree. Experience will allow identification even in the presence of severe modifications, but the development of uncommonly coarse devitrification products may destroy significant structures. The significant characteristics are discussed, and anomalous features which may lead to misinterpretation are discussed and evaluated by the use of photographs.

The minerals in these tuffs comprise the primary minerals (phenocrysts), those resulting from devitrification after emplacement, and those formed in the presence of a vapor phase. The bearing of these on the preeruption, emplacement, and subsequent mineral development is traced.

The wide distribution of ash flows, and the immense volume of the materials represented by some deposits pose many problems in volcanology. The mechanism of emplacement and physical chemistry of the deposits are considered. The source of heat required for welding has long posed a problem to geologists, but a summation of all the geologic and physical factors leads to the conclusion that no exothermic heat source is required. The inherent heat and its conservation by physical relations seems to provide ample heat for welding. The physical chemistry of the welding process is presented.

Typical occurrences of ash-flow deposits, several representative hand specimens, and a wide range of welded and nonwelded tuffs as seen under the microscope, are illustrated, and discussed where clarification of their significance is required.

INTRODUCTION

The study of volcanism as an observable geologic process, and of volcanic rocks, readily available at the earth's surface, provides a direct approach to the understanding of igneous processes and rocks. Consequently, a great deal of geologic work has been concerned with volcanism and its products, but more emphasis has been given to the lavas or flow rocks than to the fragmental rocks. One reason for this is that the pyroclastic rocks are a transitional group, composed of lava fragments, but laid down generally like sediments. These rocks have many of the characteristics of sedimentary deposits. Silicic pyroclastic rocks are, in many regions of the world, more widespread than other types, therefore an understanding of their origin is of major importance. Among these, the group known variously as ash flows, welded tuffs, glowing avalanche deposits, incandescent tuff flows, ignimbrites, and others, has been the subject of intensive study by many geologists, and several excellent papers describing specific occurrences have been published.

Throughout the literature, however, an ever-increasing diversity and duplication in terminology has been used to describe ash-flow materials, and to designate different origins, owing in part to the development of criteria for recognition, and in part to the evolution of ideas on their origin. For several years, the authors have been engaged in a detailed study of the Valles Mountains region of New Mexico where ash-flow deposits reaching a maximum thickness of nearly 1,000 feet cover more than 350 square miles. The area is dissected by many canyons where pyroclastic rocks and sections are well exposed. The experience gained in this study, supplemented by observations in many other areas of the Western United States, especially the Basin and Range province, and in Mexico, New Zealand, and Iceland, has led the authors to believe that the time is long overdue for a consideration and evaluation of the nomenclature, characteristics, and origin of ash-flow tuffs. Many ash-flow tuffs have not been mapped as such in the past because they were not recognized, and many areas previously mapped as lava flows are now known to be ash-flow tuffs. Other areas will doubtless be found after more detailed laboratory study and areal mapping. The data acquired in these studies will have more meaning if time is taken now to unravel the threads of the problem, define the terms, sort out the ideas, and reach a state, however temporary, from which further progress can be made.

This report is concerned with the results of observations of pyroclastic eruptions as reported in the literature by earlier writers. Geologic and petrologic studies of several great eruptions were made and correlated with physical and chemical data. The report also gives the nomenclature of pyroclastic materials, and describes the genetic history of ash-flow tuffs, that is, eruption, transportation, consolidation (including welding), and devitrification. Because the varied and distinguished characteristics can be more adequately and precisely described by illustrations than by words, the report contains definitive photographs of hand specimens and thin sections.

ACKNOWLEDGMENTS

Geologists who have observed and studied volcanism and volcanic rocks in many parts of the world have contributed generously during the preparation of this report, and this help, either as criticism, suggestions, advice, or specimens supplied, is here appreciatively acknowledged. Some contributions should be mentioned particularly, and first among these is the collection of 800 thin sections assembled by F. Zirkel for his petrographic studies that accompanied the geologic report on the exploration of the 40the parallel published in 1876. It is historically valuable as one of the earliest collections of volcanic rocks from the Western United States. The fine collections at the U.S. National Museum were available through the kindness of the late W. F. Foshag, curator of geology.

For many areas throughout the world that are classic localities for pyroclastic volcanic rocks, the authors have had the benefit of personal discussions with geologists familiar with the areas, or of specimens, and personal thanks are extended especially to Ivan Wilson, for ash-flow tuffs from Baja California; J. Hoover Mackin, for specimens from the Iron Springs area of southwestern Utah; W. H. Bryan, for a collection of tuffs from the Brisbane area, Queensland, Australia; the late C. N. Fenner, a pioneer in the study of ash flows, for specimens from Peru; F. G. Bonorino, for andesitic welded tuffs from Argentina; J. Bouladon, for ignimbrites from Morocco; S. Hjelmqvist, for ignimbrites from central Sweden; C. G. Johnson, H. L. Foster, H. Kuno, and T. Matumoto, for specimens from Japan; J. Westerveld, for discussions of Sumatran welded tuffs, and the late C. P. A. Zeylmans van Emmichoven, for specimens from the Toba region of North Sumatra, which were collected in 1892 by N. Wing Easton, and for specimens from the West Pasoemah region, South Sumatra, collected in 1933 by Musper and Westerveld.

NOMENCLATURE

Early in the authors' study of the Valles Mountains region, it was evident that the terminology of pyroclastic materials was inadequate. For some materials or processes, there was no term; for others, there were several. As the study and understanding of pyroclastic rocks had progressed over the years, new terms had been suggested, old terms had not been completely discarded, terms in use for certain ideas or substances had been extended in their meaning, and others were no longer applicable in their original definition. As a result, an extended examination of the terms reported in the literature has been made to face the problem of the confusion of terminology that is the natural result of work carried on in different parts of the world on a subject that lends itself so easily to differences in description and interpretation.

Two alternatives were open—either to bring together the terms in the literature, with their definitions, show how they had been used originally and evolved, and modify them where necessary by descriptive words and phrases—or to devise an entirely new systematic nomenclature which would require discarding some terms, redefining others, and coining new ones. No set of terms will encompass all the variables that are found in a highly detailed description of any group of phenomena. If specific names are proposed, there will be a need for even finer splitting, and the making of still more names. The latter course was therefore not desirable particularly for the reason that Wentworth and Williams (1932, p. 44) have put so succinctly,

> However, no great acquaintance with geologic literature is needed to be aware that only a small fraction of the terms which are proposed are destined to come into general use. The majority are only likely to add to the already burdensome list. Experience has shown that complete, systematic, novel series of terms to cover a particular field are rarely adopted.

The use of modifying words and phrases, usually requiring only 1 or 2 words to describe a variation from the norm, offers a flexibility not possible with specific terms. Thus it was decided to use the existing nomenclature and modify it by descriptive adjectives and phrases, a course that has wide acceptance and that gives others the opportunity to adapt terms to their own problems and circumstances. However, no system of nomenclature, no matter how well devised, can obviate the need for detailed description wherever that will give a more accurate picture.

Among the contributors to the development of the nomenclature of pyroclastic rocks are Blyth (1940), MacGregor (1955), Pirsson (1915), and Wentworth and Williams (1932).

The following glossary of terms gives the derivation and current usage of the term together with the authors' comments on interpretation or suggested usage.

GLOSSARY OF TERMS

Ash fall.—Deposition of volcanic ash directly from the air, generally, but not always, resulting in a stratified deposit showing crude to very complete sorting of its component parts. Unconsolidated deposits are called ash; consolidated deposits are called tuff.

The term "ash fall" has been used by Griggs (1922, p. 25), Fenner (1923, p. 26–28), Kozu (1934, p. 136), and MacGregor (1952, p. 70). Some writers use the term "airborne" to describe their material.

Ash flow.—A turbulent mixture of gas and pyroclastic materials of high temperature, ejected explosively from a crater or fissure, that travels swiftly down the slopes of a volcano or along the ground surface. The solid material in an ash flow, although unsorted, is dominantly of particles of ash size (less than 4 mm in diameter) but generally contains different amounts of lapilli and blocks.

Fisher (1954, p. 74), Taylor (1954, p. 86), and MacGregor (1955), among others, use the term "ash flow."

The flowage principle is used in industry for the transportation of solids suspended in a gas, and is known as fluidization (Work and others, 1949). Reynolds (1954) has applied the concept to the dispersal of ash-flow materials.

Ash-flow tuff.—The consolidated deposits of volcanic ash resulting from an ash flow are called ash-flow tuff. Ash flow is here used as an adjective to indicate the mechanism of dispersal, and tuff indicates the state and size of the material. Ash-flow tuff is an inclusive, general term for consolidated ash-flow beds that may or may not be either completely or partly welded.

Ash, volcanic.—Wentworth and Williams (1932, p. 45) define ash as "uncemented pyroclastic material consisting of fragments mostly under 4 mm in diameter." Blyth (1940, p. 148) described ash (volcanic ash) as "unconsolidated pyroclastic material consisting mainly of fragments less than 4 mm in size." He adds, "The use of the term 'ash' to connote a consolidated pyroclastic deposit is not to be recommended; * * * the word tuff should be used in such cases." (See *Pyroclastic materials.*)

Aso lava.—Indurated pyroclastic materials surrounding the Aso caldera of Kyushu, Japan. Matumoto (1943, p. 6) states, "The name Aso lava was originally given to the obsidian-like agglomeritic, eutaxitic, or welded mud lava * * *."

Aso lava was originally described by Iki (1899). The origin of this and many other deposits of similar materials is now well known in Japan and most of these deposits are described under the terms "welded tuffs" and "pumice flows."

Avalanche, volcanic.—The sudden avalanching of large amounts of any volcanic material down the slopes of a volcano. The term has been used by many authors, among them Lacroix (1904, p. 350) who described the material in the avalanche at Mount Pelée as being composed of earth and blocks, and by Anderson and Flett (1903) who described an avalanche of dust, sand, stones, and burnt timber at the 1902 eruption of La Soufrière on St. Vincent. Some volcanic avalanches have been described as glowing avalanches (Williams and Meyer-Abich, 1955, p. 33) where the material in them is red hot and contains gas. Other avalanches, that occur where large quantities of water are involved, are known as lahars.

Axiolite, axiolitic.—Zirkel (1876, p. 173, 176) described "linear aggregates of axially grouped fibers" as axiolites, and illustrated them in plate 7, figure 4 of that report (reproduced in fig. 95 of this report). Iddings (1899, p. 419) has given a detailed description of "axiolitic structure" as follows:

> In certain kinds of rhyolite apparently composed of welded glass fragments, there is a microspherulitic growth which bears a definite relation to the form of the supposed glass fragments. The feldspar fibers are in groups which are approximately normal to the outline of the fragments and radiate inward. Where the fragment had a rudely triangular shape the central part often attained a greater degree of crystallization than the margin, and sometimes consists of distinct crystals * * *

Marshall (1935, p. 23) has described axiolitic structures under the term "pectinate structure."

Blocks.—Blyth (1940, p. 147) defines blocks as follows: "Fragments of cognate or accidental material, larger than lapilli and usually angular, which have been erupted in a solid or nearly solid state." (See *Pyroclastic materials.*)

Block and ash flow.—See *Ash flow* and *Pumice flow.*

Dust clouds.—Airborne pyroclastic material of dust size (see *Pyroclastic materials,* also *Dust, volcanic*) that characterize explosive volcanic eruptions.

The dust clouds associated with ash flows are not basically different from glowing clouds, glutwolken, and nuées ardentes (see *Nuée ardente*) although these terms emphasize the glow that is normally reflected from the underlying incandescent ash flow.

Dust, volcanic.—Wentworth and Williams (1932, p. 47) have defined volcanic dust as follows: "Pyroclastic detritus consisting mostly of particles less than ¼ mm in diameter, that is, fine volcanic ash." Blyth (1940, p. 150) gives the dimension of dust as less than 0.05 mm. (See *Pyroclastic materials.*)

Eutaxite, eutaxitic.—Fritsch and Reiss (1868, p. 414) proposed the name eutaxite for a volcanic rock composed of ejected fragments of different colors, and texture as follows: "The different fractions in general lie beside one another as streaks, bands, and lenses in seemingly well ordered distribution."

This type of material is illustrated in figures 1 and 11. Piperno seems to be a similar rock but may, however, differ slightly by having larger lenses of glass known as fiamme.

Fiamme.—The Italian name used to describe black glassy inclusions in piperno and which have a cross section shaped like tongues of flame. These are often several centimeters in length, but may range from microscopic size to several feet in length.

Zavaritsky (1947, p. 11) has proposed to include all such glass lenticles (collapsed pumice fragments) under the term "fiamme." Matumoto (1943, pl. 24) illustrates "obsidian spindles" in the "Aso lava" from the Aso caldera of Kyushu, Japan.

Fluidization.—See *Ash flow.*

Glowing avalanche.—See *Avalanche, volcanic.*

Glowing clouds.—See *Dust cloud,* also *Nuée ardente.*

Glutwolken.—See *Dust cloud,* also *Nuée ardente.*

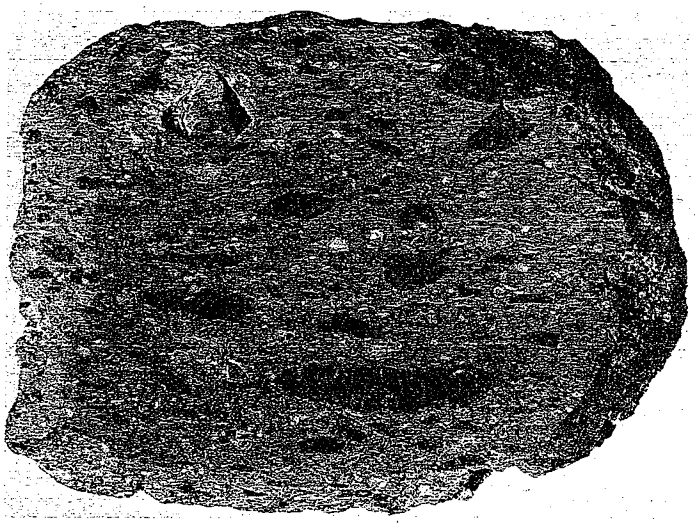

FIGURE 1.—A specimen from the Battleship Rock tuff (fig. 3) north-northeast of Jemez Springs, N.Mex. This represents the thoroughly welded part, and figures 42 and 43 represent specimens from the nonwelded basal part of the same flow. In the nonwelded tuff the pumice contains about 70 percent of pore space, while in this specimen there has been complete collapse and welding with the elimination of all pore space. The black lenses of collapsed pumice in a fine-grained groundmass represent the structure known as piperno.

Ignimbrite.—Marshall (1935, p. 4–10) proposed the name "ignimbrite" (literally fiery rain cloud rock). He defined ignimbrites (1935, p. 1) as follows:

> * * * they are thought to have been deposited from immense clouds or showers of intensely heated, but generally minute fragments of volcanic magma. The temperature of these fragments is thought to have been so high that they were viscous and adhered together after they reached the ground.

Elsewhere he states (1935, p. 38),

> Ignimbrite is used as a name for a tuffaceous rock of acid composition that has been formed from a 'nuée ardente Katmaieene' in the nomenclature suggested by A. Lacroix.

Thus Marshall visualized ignimbrites as a rock of "acid composition" formed by the fall from a cloud of hot viscous material. The term "ignimbrite" has been used by Bonorino (1944), Bouladon and Jouravsky (1955, p. 25), Hjelmqvist (1956), and others.

Incandescent tuff flow.—Fenner (1948a, p. 879) described the "tuff flows" of the Arequipa region of Peru as "incandescent tuff flows," and stated, "The tuff deposits are the result of a series of fragmental outbursts of rhyolitic lava, similar to that which occurred in the Valley of Ten Thousand Smokes in Alaska." He also stated (1948a, p. 882), "An especially important feature * * * is the ability of such tuff flows to spread widely over level or gently inclined surfaces." Jenks and Goldich (1956, p. 156) use the term "tuff flows" for the same deposits.

"Tuff" is not a suitable term to describe unconsolidated material (see *Tuff;* also *Ash, volcanic*) during flowage. Only after emplacement and consolidation should the material properly be called "tuff."

Lahar.—A term used in Indonesia to designate a volcanic mudflow. The term has been used by Curtis (1954, p. 458) "* * * for any volcanic breccia with a matrix of tuffaceous aspect which came to rest as a single unit and was originally mobilized by addition of water, gravity alone being the motivating force." Lahars may originate in different ways such as mobilization of rain-soaked debris on volcanic slopes (cold) or by eruption through crater lakes (hot) (van Bemmelen, 1949, p. 191). Hot lahars may also be initiated by nuées ardentes entering streams.

Lapilli.—Wentworth and Williams (1932, p. 33) state, "According to most writers they [the lapilli fragments] may consist either of juvenile lava, still liquid or plastic when ejected, or of broken rock of any sort from the walls of the vent or from the bed rock; that is, they may be essential, accessory or accidental ejecta." Blyth (1940, p. 147) describes lapilli as "Cognate or accidental ejecta ranging mainly from 32 to 4 mm in size." (See *Pyroclastic materials.*)

The lapilli of ash-flow tuffs are commonly pumice fragments, as are most included blocks, but accidental rock fragments may also be present.

Mudflow, volcanic.—Volcanic mudflows or lahars are not basically different from nonvolcanic mudflows except for the volcanic origin of their materials. Nonvolcanic mudflows or "mud spates" have been described by Rickmers (1913, p. 195) as follows:

> It is not dry nor is there much water, but the whole mass appears like a rapid flush of mud, although frequently the rock waste is so rough as to suggest that it is properly mud. Enormous boulders will float in this thick porridge.

The term "mudflow" was also applied to ash flows before they were fully understood. Thus Marsters (1912) called the ash flows of Peru "mudflows" and Griggs (1917, pl. 2) in his early studies of the volcanic deposits of the Valley of Ten Thousand Smokes called this material "mudflow." This was later called "sand flow" by Griggs and "tuff" deposit by Fenner (1923).

Mud lava.—The term "mud lava" has been used to describe some materials in Japan which are now known to be ash-flow materials. Matumoto (1943, pl. 30) referred to welded mud lava. (See *Aso lava.*)

Nonwelded tuff.—The term "nonwelded tuff" will be applied to those ash flows or parts of ash flows that have not become welded. The mode of deposition and consequent cooling of ash-fall materials precludes welding, in contrast with ash-flow materials which may or may not become welded. Thus there should be no confusion, and it seems unnecessary to use the term "nonwelded ash-flow" materials each time they are mentioned. That is, "nonwelded tuffs" are always to be understood as the corollary of welded tuffs.

An alternative would be to extend the term "sillar" (see *Sillar*) to include all nonwelded tuffs. Fenner (1948a, p. 883) proposed this name for the poorly indurated tuffs of Peru, but did not suggest its use as a general term for these materials. Also, some of the tuffs of Peru that were included as sillars seem to have undergone slight welding. However, one of the principal characteristics of the Peruvian tuffs is induration by vapor-phase crystallization. This was recognized by Fenner and it may be that this term could be more appropriately used for tuffs indurated by this process than as a general term for nonwelded tuffs. The term "sillar" has been used by Barksdale (1951) and Williams (1952, p. 176) for nonwelded ash-flow tuffs.

Nuée ardente.—Lacroix (1903a, p. 442–443) proposed the term "nuée ardente" to describe the previously unrecognized type of volcanism that characterized the eruptions of Soufrière and Pelée in 1902. Lacroix (1904, p. 350) describes the eruption at Pelée as follows:

> A nuée ardente is made up of an emulsion of solid materials in a mixture of water vapor and gas at high temperature, about the nature of which I shall not refer. The shape and dimensions which it presents at the moment of its emission from the carapace of the dome, show that it has been subjected to an enormous pressure, for after a few seconds, it occupies a volume greater by many thousand times that which it had at its inception.

He also says,

> At the base [of a nuée ardente] is found a zone at very high temperature, in which the solid materials predominate (blocks of all dimensions, very small fragments, fine cinders); each of these pieces, or the solid particles of which it is formed, radiate heat, and must be surrounded by an atmosphere of gas and vapors, extremely compressed at the beginning, but expanding rapidly; it is this atmosphere which prevents the solid particles from touching one another, maintaining the mass in a state of mobility which allows it to flow over the slope almost in the manner of a liquid.

The term "nuée ardente" is well established as the name for a type of volcanic eruption, a usage with which we are not concerned (see *Pelean eruptions*). We are, however, concerned with an understanding of the mechanism of deposition of welded tuffs. The second part of the quotation from Lacroix shows that he clearly recognized the dual character of the nuée ardente—the overriding dust clouds, and the dense basal part. The full significance of the concept of Lacroix has not always been understood.

Perret (1937, p. 5) pointed out the common failure to recognize the dual character of nuées ardentes in the following statement:

> The term nuée ardente for want of something more precisely descriptive, has been quite generally adopted. '*Nuées ardentes*' as well as '*Glutwolken*' and '*Nuages denses*' all refer in too restricted a sense to the *cloud* aspect of the phenomenon, losing sight entirely of the source of energy *within the avalanche*, the inherently active mass of denser material, hidden, all but completely, by the magnificently spectacular convolutions of vapor and ash * * *.

Again (1937, p. 20) in describing the eruptions of January 5, 1930, he states,

> A strong west wind * * * moved the ash cloud above, while the heavy mass of the avalanche beneath was quite unaffected. The dust cloud * * * was not only checked, but forced backward even beyond the point of issue.

Figure 2 shows the dual character of a Pelean nuée ardente.

Fenner (1948a, p. 881) made the following comment:

> The terms 'nuées ardentes' and 'glowing clouds' were applied to these phenomena, but though these clouds are spectacular and terrifying, to call the whole group of actual manifestations 'nuées ardentes' tends to place the emphasis on the relatively superficial clouds that rise from the plunging mass rather than on the mass itself * * *.

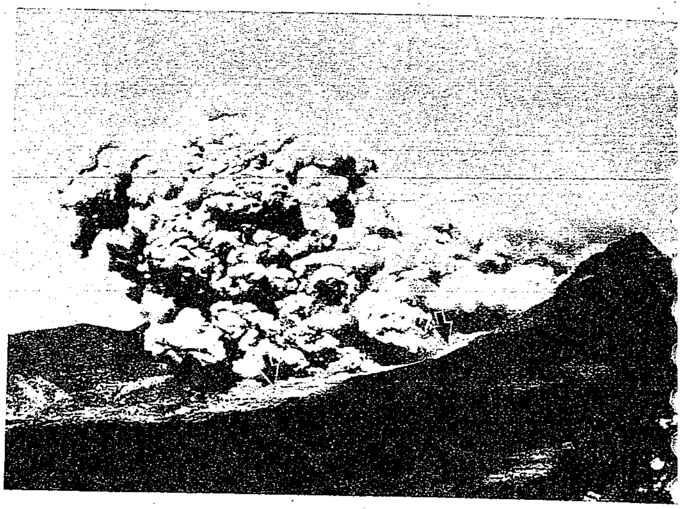

FIGURE 2.—A "small typical nuée ardente" of Feb. 8, 1930, at Pelee, illu trated by Perret (1937, fig. 16). The arrows indicate the ash-flow par of the nuée ardente which has sped in advance of the overriding du clouds.

Notwithstanding the well-established recognition (beginning with Lacroix) of the dense basal part of an ash flow as the effective medium of transportation, the strictly airborne concept has found its way into some geologic interpretations, and beclouded the whole approach. The geologist must study and interpret the deposits formed by the dense underlying part of the eruptions, and is in need of clearly distinguishing terms. This means that, as MacGregor (1955, p. 10) has pointed out, "* * * the classification of nuée ardente eruptions should be quite distinct from the classification of the products produced by such eruptions [and including the mechanism that emplaces these products]."

In summary, nuée ardente has come to have two distinct usages; one for a special type of volcanic eruption, and the other for the clouds that ordinarily accompany these eruptions—glowing cloud being the commonly used English equivalent. Usage has not always differentiated between the clouds themselves and the dense ash- or block- and ash-transporting basal part. If so used, this basal part would constitute the noncloud portion of a glowing cloud, which may not even be glowing. In general, it glows only by reflecting the incandescent underlying ash flow.

Obsidian spindle.—See *Fiamme.*

Pectinate.—See *Axiolite.*

Pelean eruption.—This term has been used to describe certain types of eruptions resulting in ash-flow or avalanche deposits, and similar terms have been proposed for several other types of volcanic eruptions. The classification of types of eruption has been outlined by Lacroix (1930), Fenner (1937, p. 236), Perret (1937, p. 3–5), and Williams (1941b). A detailed classification has been presented by MacGregor (1952, tables 1 and 2). These terms are widely used in descriptions of the eruptions of active volcanoes, but have also been applied to older ones where the character of the eruption could be verified.

Piperno.—A rock first described from the Phlegrean Fields in Italy is locally known as piperno. It is characterized by conspicuous lenses of glass (fiamme). "Pipernoid" is a phase of the same rock in which a similar structure is revealed under the microscope.

Dell'Erba (1892), and later Zambonini (1919, p. 72), concluded that piperno was a tuff, and was deposited at a high temperature. Rocks of this texture are illustrated in figure 1.

Pumice.—Webster's New International Dictionary (1933, p. 1735) defines pumice as follows: "A highly vesicular volcanic glass produced by the extravasation [more properly exsolution from the glass] of water vapor at a high temperature as lava comes to the surface: hardened volcanic glass froth." Wentworth and Williams (1932, p. 39) quote Lacroix (1930, p. 437) as follows:

> The glass is not only puffed up, but spongy, drawn out, sometimes fibrous or filamentous; the cavities are extremely abundant and their form varies according to the composition. The types with elongated, tubular parallel vesicles have a fibrous or silky aspect; these are characteristic of rhyolite pumice, whereas the cavities are more or less spherical in trachytic and phonolitic pumice.

The term "pumice" implies no specific size of materials and a pumice structure is retained by some ash-size materials. In general, however, explosive eruption has disrupted the original vesiculated magma into individual segments of the cell walls, and so the distinctive pumice structure has been destroyed to form glass shards. The material which results is known as volcanic ash. (See *Ash, volcanic.*) If the retention of pumice structure is conspicuous the material could be called a pumiceous ash.

Pumice fall.—Deposition of pumice directly from the air. (See *Ash fall* and *Tephra.*)

Pumice flow.—Flows with a conspicuous proportion of pumice fragments of lapilli size (4 to 32 mm) or block size (>32 mm) have been called pumice flows. (See *Pyroclastic materials.*) Tsuya (1930) applied the term "pumice flows" to the materials formed by the 1929 eruption of the Komagatake volcano in Hokkaido, Japan. Other Japanese geologists, including Kozu (1934, p. 136) and Kuno (1941, p. 148), have described pumice flows. As used by the Japanese geologists "pumice flow" is synonymous with "ash flow."

Flows characterized by coarser material have been called lapilli flows, and block flows. Williams (1942, p. 79) referred to the Crater Lake "glowing avalanches" as "pumice flows" and "scoria flows." Perret (1937, p. 5) applied the term "block and ash flow" to some materials at Pelée.

Pumiceous ash.—See *Pumice.*

Pyroclastic.—Wentworth and Williams (1932, p. 24) state, "Pyroclastic is an adjective commonly applied to rocks produced by explosive or aerial ejection of material from a volcanic vent." The noun form pyroclasts is defined by Holmes (1920 p. 193) as "A general term for fragmental deposits of volcanic ejectamenta, including volcanic conglomerates, agglomerates, tuffs, and ashes." (See *Tephra.*)

Pyroclastic materials.—The following size classification of volcanic fragmental materials is given by Wentworth and Williams (1932), and by Blyth (1940):

Size classification of volcanic fragmental materials, in millimeters

Name	*Wentworth and Williams (1932)*	*Blyth (1940)*
Block	>32	>32
Lapilli	Mostly 32 to 4	32 to 4
Coarse ash	4 to ¼	4 to 0.5
Fine ash	<¼	0.5 to 0.05
Volcanic dust		<0.05

Wentworth and Williams, and Blyth are virtually in agreement, except that Blyth preferred decimal fractions, using the figure approximating the value of the common fractions used by Wentworth and Williams.

Sand flow.—Griggs (1922, p. 253–254) describes the "great hot sand flow" as follows:

> The bulk of the deposit is composed of fine fragments, many of them dust-like, but there are included numerous lumps of pumice which in places make up a considerable fraction of the whole. There is no trace of stratification of the materials, except where they were obviously subject to secondary readjustments after deposition * * *. At the foot of the valley we found clear-cut and positive evidence of the manner of the tuff making it certain that the sand of which it was composed must have flowed down the valley like a viscous liquid.

Griggs (1922, p. 261) also referred to the tuff as "the incandescent sand flow."

Scoria flow.—See *Pumice flow.*

Sillar.—Fenner (1948a, p. 883) in describing the "incandescent tuff flows" of Peru writes,

> For those [tuffs] in which induration is primarily the result of recrystallization, and for those in which the fragments have little cohesion, another term is desirable [that is, other than welded tuffs]. The local term 'sillar' (pronounced seelyár), commonly used in the Arequipa region, has been applied in the present paper.

Tephra.—Thorarinsson (1955, p. 12) proposed "the term tephra as a collective term for all clastic volcanic material *transported from a crater through the air* * * *."

Tuff.—Wentworth and Williams (1932, p. 50) define tuff as "indurated pyroclastic rocks of grain generally finer than 4 mm, that is, the indurated equivalent of volcanic ash or dust." (See Blyth, 1940, p. 153; also *Ash, volcanic,* and *Incandescent tuff flows.*)

Tuff lava.—Abich (1882, p. 39) described the rocks of the Alaquez massif, Russian Armenia, as "tuflava," and Zavaritsky (1947, p. 12) has used the same term and shown that the materials are characteristic welded tuffs.

Tuff, crystal.—In describing crystal tuffs Pirsson (1915, p. 199) states,

> Tuffs composed entirely of crystals, must be very rare * * *. On the other hand, crystals of minerals, the kinds depending largely on the nature of the magma, either perfect in form or more or less fragmental, are found in nearly all tuffs; and when they become a dominating or striking feature of them the rocks are referred to as crystal tuffs.

Crystals or crystal fragments characterize almost all ash-flow tuffs and range from a trace to more than 50 percent of the rock in some tuffs.

Tuff, lithic.—In describing lithic tuffs Pirsson (1915, p. 201) states that "The essential feature of tuffs of this class is the presence in them of a striking or dominating degree, of fragments of previously formed rocks * * *. These fragments may be holocrystalline or partly glassy."

Rock fragments are present in nearly all ash-flow tuffs but rarely exceed a few percent of the rock.

Tuff, vitric.—A name proposed by Pirsson (1915, p. 194) for "Tuffs produced by the sudden and violent explosion of a more or less viscous magma * * *. The explosion of gas and rupturing began in a liquid medium; the resulting product falls as a rigid glass."

In general, ash-flow tuffs are dominantly vitric or derived from originally vitric material. As Pirsson states, such material would fall from the air as a rigid glass (ash-fall tuffs). However, where flowage occurs, the glass may retain plasticity until after deposition.

Tuff, welded.—Mansfield and Ross (1935, p. 308, 321) described

> welded volcanic tuffs—that is, those in which individual fragments had remained plastic enough to become partly or wholly welded * * *. In a few specimens the original forms are unmodified; in others there is flattening, but without obliteration of characteristic ash structure; and in a few, extreme flattening and slight flowage has almost obscured the original structure.

The term "welded tuff" is self explanatory, and has been widely used by many geologists including Gilbert (1938, p. 1851), Westerveld (1942), Williams (1942, p. 60), and Enlows (1955). Bodenhausen (1955, p. 44) used the French form of the same term (tufs cineritiques soudes).

Welded pumice.—Collapsed pumice has been called welded pumice by Iddings (1899).

The materials called welded pumice by Iddings are discussed in detail on pages 11–12 of this report. The full relationships of these materials were not fully understood by Iddings, but the subject of welding interested him greatly, and he returned to it several times. Iddings is widely recognized as discovering the phenomenon of welding, and of having proposed the term "welded pumice," although the term "welded" was used long before by Zirkel (1876, p. 267).

DEVELOPMENT OF CONCEPTS

Present-day concepts of the origin of ash-flow tuffs and of processes which lead to welding in these rocks have developed through a series of disconnected observations and events over a long period. An attempt is made here to integrate a series of early interpretations, key studies, and important natural events into a chronology showing the general evolution of thought regarding these rocks.

A review of the literature indicates that welded tuffs have caused much speculation and difference of opinion among geologists at least as far back as the late 1860's. Several workers have been confronted with rocks that showed most of the characteristics of pyroclastic materials and yet, in the light of existing knowledge, could only be explained as lava flows. There was at times actual controversy, one man claiming the rock to be a tuff, and the other one calling it a peculiar type of lava.

Many rocks have been described that show peculiar "flow" structures or "ash" structures, or what has been considered normal "rhyolitic" structure. Many of these rocks, from their descriptions, illustrations, or by reexamination, are now known to be welded tuffs. The writers believe that the attempts of some of the early workers to interpret these materials are an essential part of the historical background of welded tuffs. Thus the following review will include quotations from the older works as well as discussions of the papers dealing directly with welded and nonwelded ash-flow tuffs, and the relations of these rocks to volcanic eruptions of "Pelean" and "Katmaian" type. Special emphasis is given those older works where reexamination by the authors or by other workers has shown what is probably the true nature of the rocks described.

Fritsch and Riess (1868), working on Tenerife, one of the Canary Islands, described rocks that they named eutaxites. These rocks, which to the authors' knowledge have not been reexamined, seem almost certainly to have been welded tuffs or at least welded clastic rocks. This seems to be one of the first recorded examples of an attempt to understand the origin of such rocks and is important because from this work comes the term "eutaxitic." This term has since been used by many authors in different ways but has come to be applied most frequently to the structure seen in many welded tuffs (fig. 1). For further discussion of this term see page 4.

During 1867–78, those engaged in the U.S. Geological Exploration of the 40th Parallel, under the leadership of Clarence King, made extensive collections of rocks in several of the Western States. These rocks were studied petrographically by Zirkel (1876) and the field studies were discussed by King (1878). Of the more than 2,500 thin sections studied by Zirkel, the authors do not know how many were of rhyolitic rocks. However, more than 800 of these thin sections are now in the collections of the U.S. National Museum. Reexamination of these sections by the authors has revealed that nearly 200 are of welded rhyolitic tuffs, most of which came from the 40th parallel in Nevada (figs. 93 and 94). Many of Zirkel's descriptions and illustrations (see reproduction in fig. 95) are clearly those of welded tuffs. It is doubted that Zirkel observed anything unusual about the origin of these rocks, but he did observe many textures that were new to him.

Zirkel (1876, p. 163) says of the rhyolites in general,

> Of all the rocks, these rhyolites most excel in variety and diversity of microscopical structure; and since better facilities for investigation than had ever before been enjoyed, were furnished by the extraordinary number of occurrences at hand, it is highly probable that the following pages will be found to explain all, or nearly all, the most characteristic types of which the rhyolitic structure is capable. Particular attention has been paid to these interesting varieties, examples of which will doubtless be found in studying the comparatively unknown rhyolites of other countries.

Zirkel has given one of the most remarkable accounts of variations in texture in welded tuffs ever presented, but he was unaware of their true origin. From Zirkel's work has also come the term "axiolitic" which he applied to a certain type of devitrification in glass shards. This structure is common in certain welded tuffs and is discussed on pages 4 and 37, and illustrated in figures 71–74.

King (1878) gives detailed megascopic descriptions and accounts of the field occurrences of the rocks that had been studied petrographically by Zirkel. Several welded tuffs are discussed under the classification of breccias and cemented breccias by King. The reader is profoundly impressed by these accounts and by the widespread distribution of these rocks in the Western United States, especially in Nevada.

Dell'Erba (1892), in a report on the origin of the much discussed piperno of Italy, concluded that this rock was a tuff rather than a lava as had been supposed by other workers. He also concluded that it had been hot at the time of its deposition. Piperno contains many lenticular fragments of black glass known locally as fiamme and Dell'Erba thought that it was these fragments that supplied the heat, the effects of which could be seen in certain peculiar characteristics of the tuff. Dell'Erba deserves great credit for recognizing that this rock had a pyroclastic origin.

Several studies of the Italian piperno, particularly those of Zambonini (see p. 12 of this report) and of Zavaritsky (see p. 14), suggest that these lenticular glass fragments are collapsed and strongly welded pieces of pumice (fig. 1).

Turner (1894), in discussing some of the rhyolites of the western slope of the Sierra Nevada in California, says,

> The rhyolite flows evidently followed the old river channels to a remarkable extent. The exact nature of these flows is not in all cases determined. They have been considered as tuffs or mud flows, but in thin section some specimens show trains of spherulites and other evidences of having been molten lava.

Reexamination of similar and probably related rhyolites on the western slope of the Sierra Nevada by several workers indicates that these rocks can now be regarded as welded tuffs.

Ransome's (1898) study of a series of volcanic rocks of the western slope of the Sierra Nevada in California, provides the most outstanding example of careful consideration, indecision, and wrong conclusion caused by a welded tuff, that has yet come to the attention of the authors. Among the volcanic rocks Ransome discovered one that he named "biotite-augite latite." He seems to have had difficulty classifying it from the very beginning, and says of his rock (1898, p. 27),

> * * * the biotite-augite latite has characteristics that render its distinction from a tuff not always easy. The fact that it has a wider distribution than the two undoubted massive flows, also suggests that it may have had a different origin. But the field evidence does not support the view that it is in any sense a water-deposited tuff. It is entirely devoid of the horizontal bedding characteristic of the known tuffs of the region, and on the other hand it possesses the more or less uneven upper and lower surfaces, and the ability to lie upon perceptible slopes, which are characteristics of true lava streams. It also resembles lavas in being coarsely columnar in structure, although, as has been shown this structure may also occur in undoubted tuffs. The basal contact of the biotite-augite latite was nowhere seen sufficiently well exposed to give a decisive answer to the question whether it is tuffaceous or massive in character.

The next quotation (Ransome, 1898, p. 42–44) is long, but is so pertinent to an understanding of the problems that faced earlier students of these rocks that the authors believe it should be included. This quotation not only indicates the views of some of the earlier European geologists, but shows the intensity of Ransome's thinking on the controversial nature of some tuffs and lavas.

> The general microstructure of the biotite-augite latite appears to approach very closely to the *eutaxitic* structure as the term was first employed by Fritsch and Reiss (1868), who applied it to certain facies of phonolites, andesites, and trachytes possessing some resemblances to clastic rocks and inclosing undoubted clastic fragments. They distinguished *agglomerate lava,* in which the structure was supposed to be due to partial refusion of clastic material, from *piperno,* in which portions of the magma in different stages of crystallization are brought into juxtaposition by the motion of the flow: Common usage, however, has somewhat altered the original application of the term *eutaxitic,* so that it frequently implies merely a fluidal banding brought about by alternating streaks of microfelsitic and clear glass (Zirkel 1893), or is even used as 'a general name for banded volcanic rocks' (Kemp 1896). That such can hardly have been the earlier application of the word appears from the discussion that has centered about the original *piperno* of Pianura in the Phlegraean Fields, near Naples, a rock that Fritsch and Reiss took as the second type of eutaxitic structure, and which appears to resemble in some ways the biotite-augite latite of California. Luigi dell'Erba (1892) considers this rock a tuff, but the greater number of petrographers have regarded it as a lava flow. Zirkel (1893) refers to it as a sanidine trachyte with eutaxitic structure, remarking that Luigi Dell'Erba's view is not even probable, while Rosenbusch (1896) cites it as an example of his Ponza type of the trachyte family. Such a discussion could scarcely have arisen were the structure concerned a simple banding such as is observed in many vitrophyres, and which no petrographer could for a moment regard as indicating a tuffaceous origin. Kuch (1892), following the terminology of Reiss, describes both kinds of eutaxitic structure, the agglomerate lava and the piperno, as occurring in the dacites and andesites of Colombia. The latter form is particularly abundant, and Kuch remarks that it is at times impossible to distinguish the two varieties, as the piperno often contains included fragments of other andesites. Wickmann (1897), in describing an augite-mica-andesite from the Indian Archipelago having a structure apparently nearly identical with that of the biotite-augite latite of the preceding pages, refers to it as having piperno structure; and there seems to be little doubt that this latter name, as used by the petrographers cited, expresses accurately the structure of the second flow of the Sierra Nevada latites.
>
> When, on the other hand, a thin section of the last-named rock is compared with that of a lava having typical flow banding—as, for example, the beautiful vitrophyre of San Lugano, in the Tyrol, or the pitchstone-vitrophyre occurring between Lake Lugano and Lago Magiore, both of which, according to Rosenbusch (1896), often show eutaxitic facies —the chief difference seems to lie in a greater irregularity and brecciation of the bands in the latite, and in the presence of included rock fragments.

In a later paragraph Ransome (1898, p. 44), says,

> As an historical illustration of the difficulty that sometimes exists in distinguishing a tuff from a massive lava may be recited the case of the so-called 'peperino' near Viterbo, in Italy, which, according to Washington (1896), is probably a tuff, although it possesses some apparent flow structures, and has been by earlier investigators frequently designated a massive rock.

As a result of reading the writings of Ransome on the biotite-augite latite and a group of associated rhyolites, Smith reexamined these rocks in the field in 1950 and concluded that they were welded tuffs.

The biotite-augite latite shown in figure 82 is from an exposure near McKays, Calaveras County, Calif. This rock is a fine example of a crystal-rich, glassy, welded tuff and after examining it in the field and laboratory it is not difficult to understand Ransome's uncertainty about it. He finally concluded it was a lava because at that time no volcanic mechanism was known that might produce a rock intermediate between a lava and a tuff.

Part of the group of rhyolites studied by Ransome are located near Altaville and Vallecito, Calaveras County, Calif., and are within an area recently mapped by Lorin Clark (oral communication, 1950) of the U.S. Geological Survey. These rocks have been recognized by Clark as welded tuffs, and are probably closely related to the rhyolites discussed by Turner (1894), and the welded tuffs mentioned by Curtis (1954, p. 453–454).

The studies of Diller and Patton (1902) of the volcanic rocks of the Crater Lake region give us one more example of the uncertainties of nomenclature attached to these rocks. In writing of the Wineglass dacite flow Diller says,

> This peculiar tuffaceous dacite occurring along much of the crest of the rim all belongs to one flow, which spread as a uniformly thin sheet over that portion of the base of Mount Mazama. It is altogether unlike the other flows of dacite and appears to be intermediate between them and tuff.

Reexamination of this same dacite was made by Williams (1942) and shown by him to be a welded tuff.

The first major contributions to the understanding of welded tuffs were the works of Iddings (1885–86, 1899, 1909), an outgrowth of his studies of the volcanic rocks of Yellowstone National Park (figs. 87–89, 91 and 92). He must be credited with developing the concept of welding of pyroclastic materials as well as being the first to use the term "welded pumice." His first use of the term "welded" seems to have been in connection with a specimen from the rhyolite flow of Obsidian Cliff. The following quotation is important only because it seems to have been Iddings' first recorded use of the word "welded," and his concepts of welding of hot clastic rocks apparently developed from that time. Iddings says (1885–86, p. 274), in reference to colored bands in obsidian,

> In some the colored streaks are in broad, thin bands, either straight or twisted, according to the last movements of the viscous glass. In others, they are in the most delicate threads, alternating with streaks of black grains running continuously through the rock, though sometimes interrupted by streaked patches of other character or appearing as though the rock had been broken into fragments and welded together again (pl. 16, fig. 2).

This figure is reproduced in this report as figures 87 and 88.

This rock from the Obsidian Cliff rhyolite flow is not a welded tuff, but rather a welded breccia which is not uncommon on the margins of rhyolite domes and flows or in sheared zones in rhyolite flows. Such welded breccias may often superficially resemble coarse-grained welded tuffs, especially if they are composed of pumiceous fragments. In a more detailed study of the rhyolitic rocks from Yellowstone National Park, Iddings (1899, p. 403–404) says in relation to pumice, "In some instances it is evident, from the confusedly twisted and curved arrangement of the glass fibers and films, that the inflated glass mass settled back upon itself, or collapsed, after the escape of much of the gas." To explain this interpretation of his observations he says, "When we remember the enormous extent of many of the streams of rhyolite in this region, we may easily imagine the formation of pumice over the surface of an intensely heated area of lava, thus permitting its subsequent welding."

These statements were made with reference to collapsed or deformed pumices, rather than to the typical shard structures of welded tuffs. However, Iddings states (1899, p. 405–406),

> In numerous cases a pumiceous character is entirely wanting. The mass is a compact glass, but it consists of irregularly shaped streaks and patches of different color. These twist and curve about one another and appear like a perfectly welded mass of strips or ribbons and irregular fragments of variously colored glass. In some cases their shape closely resembles that of fragments of pumice pressed together and welded (pl. 50, figs. 1, 2, and 3). In others it appears as though such fragments had been drawn out and twisted by a movement of the mass (pl. 51, fig. 2). Undoubtedly this has been the case, but it is doubtful whether all the streaked and variegated glasses have passed through the process of inflation, collapse, and welding with subsequent flow. However, the distinctly outlined and strongly contrasted streaks and ribbons of variously colored glass, are with difficulty explained in any other manner.

Although Iddings recognized the phenomenon of the welding together of vitric fragments, he apparently was uncertain as to the causes of welding and the origin of the resulting rocks. This is understandable since Iddings' accounts show that he was dealing with three processes of welding. These processes are: (a) the brecciation of glass in shear zones, or at the base of rhyolite flows and the subsequent welding of the resulting breccia; (b) the formation of pumice on the surface of lava flows and the deformation or collapse of such pumice due to the heat from the flow and its subsequent movement. Although some of Iddings' "welded pumice" was formed in this manner probably many of the rocks examined by Iddings and believed by him to have formed in such a way were true welded tuffs; (c) the explosion of material from a vent into the air, the fall of the material while still hot back into the vent, and its subsequent welding, followed by extrusion from the vent in the manner of a lava. Concerning the third process, Iddings (1909, p. 331) says,

> When exploded fragments of molten magma, large or small, fall together in a still heated condition, as may readily happen within the crater of a volcano or in the mouth of a fissure, they may be plastic enough to weld together into a more or less compact, coherent mass. This may subse-

> quently flow like other lava, and is known as FLOW-BRECCIA. * * * [1909, p. 333] The same operation may result in the welding of exploded pumice, or of collapsed pumice that was highly inflated. The distinction between this and a flow breccia is chiefly in the size of the welded fragments.

The explanations given by Iddings are inadequate to explain the process of welding involved in the formation of welded ash-flow tuffs but they are important historically.

Twenty-two of the original thin sections studied by Iddings are still available and some of the best of these are shown in the frontispiece, figures 88, 91, and 92. Although more than 50 years old, they are very well preserved. It is very fortunate that the thin sections, which were the basis for Iddings' recognition of the fact of welding together of fragments of glassy pumice and ash and for his proposal of the name "welded pumice," are still available.

The eruptions in May 1902, of Mount Pelée on the Island of Martinique and of La Soufrière on the Island of St. Vincent, marked a turning point in the understanding of the mode of formation of many of the world's deposits of pyroclastic rocks. The observations made at Sufrière and Pelée by Anderson and Flett (1903), and at Pelée by Lacroix (1904), and at a later date by Perret (1937), gave to the science of volcanology an understanding of a new type of volcanic eruption, and formed the basis for the present-day concepts of the origin of ash-flow materials, including welded tuffs. The studies of Anderson and Flett, Lacroix, and Perret are discussed on pages 15–16 in this report.

The pyroclastic deposits formed by the eruptions of Pelée and Soufrière are characterized by their complete lack of sorting and at Pelée, at least in part, by the widely variable dimensions of the constituent blocks, fragments, and dust. Such deposits came to be known as Pelean tuffs and in the years following the eruptions of 1902 several writers described tuff deposits from other parts of the world and attributed their origin to eruptions of Pelean type. Dakyns and Greenly (1905) seem to have been the first to further develop the concept in a paper on the "felsitic slates" of Snowdon, Wales. In an earlier paper Dakyns (1900) had recognized that these rocks were clastic and concluded that they were "felsite tuffs." Greenly, inspired by the account of Anderson and Flett on the eruptions of Pelée and Soufrière, sought to reconcile certain unexplained features of the Snowdon rocks with the observed features of the ejecta of Pelée and Soufrière. In so doing, he concluded that the Snowdon felsites were due mostly to eruptions of Pelean type. Greenly says of these rocks (Dakyns and Greenly, 1905, p. 548), "* * * in the felsitic slates of Snowdon we have a Pelean deposit of the Ordovician period."

Lacroix (1906, p. 1020–1022) attributed a Pelean origin to a group of ancient volcanic rocks of the Auvergne region in France.

Zambonini (1919) reviews the problem of the origin of the Italian piperno and concludes, as had Dell'Erba, that it is a tuff and that it was deposited in a hot condition as shown by the occurrence of several late-stage minerals, some of which contain fluorine. He also concludes that it probably originated as a "Pelean cloud" deposit.

Although the eruptions of Mount Pelée and Soufrière and the observations by Anderson and Flett, Lacroix, and the later studies by Perret were of fundamental importance in establishing a new type of volcanic action, and especially a new mechanism for the transportation of pyroclastic materials, it was the formation in 1912 of the "sand flow" in the Valley of Ten Thousand Smokes, Alaska, accompanying the eruption of Mount Katmai, that provided the necessary link for our present understanding of the origin of ash- and pumice-flow materials in general.

The first account of the discovery of the Valley of Ten Thousand Smokes and its now famous deposit of volcanic ejecta, by members of a National Geographic Society Expedition was by Griggs (1917, p. 12–68). In a series of papers Griggs (1917, 1918a, b, c, 1919, 1921, 1922) discussed other phenomena of the region and the deposit of volcanic tuff which he termed the "great hot mudflow" (Griggs, 1918b).

Fenner (1920) and his associates, especially E. G. Zies of the Carnegie Institution of Washington Geophysical Laboratory, noted the effects of heat as shown by the so-called mudflow, but were unable to reconcile the observed heat effects with hot water-bearing mud and concluded that the deposit, while rich in gas, was virtually dry and called it the "great sand flow" (fig. 96). Fenner (1923) finally concluded that the sand flow was deposited as a mixture of gas and ash and was similar in many respects to the deposits formed by the eruptions of Pelée and Soufrière. However, he noted a difference in the materials deposited and therefore considered them to be the result of a type of, or modified, Pelean eruption. This conclusion has had a marked influence on nearly all the geologists who have subsequently worked with ash-flow pyroclastic materials because, in comparing most welded tuffs and their nonwelded equivalents with the deposits of Pelée and the Valley of Ten Thousand Smokes, a greater similarity is seen with the sand flow than with the Pelean deposits.

As an example of this comparison Williams (1927), in a detailed study of the rocks of Snowdon, Wales, discusses the origin of some rhyolites that Dakyns and Greenly had previously concluded were tuffs formed from an eruption of Pelean type. Williams noted that the tuffs were composed largely of glass fragments and glass dust rather than crystals, which are more typical of Pelean tuffs, and concluded that while they were probably erupted in a manner somewhat analogous to the Pelean ejecta, they resembled more strongly the rhyolite tuffs of the Katmai area.

Moore (1934) discusses the probability of a nuée ardente origin for the "older" pumice of Crater Lake, Ore., as opposed to an origin of direct fall from the air as shown by the "younger" pumice. His conclusions are based on several differences between the two types, especially with regard to size and sorting. The younger pumice is more uniform in size and is better sorted, whereas the older pumice is widely variable in size and shows no bedding or sorting.

The work of Marshall (1932, 1935) on the vast deposits of rhyolitic tuffs on the North Island of New Zealand is a milestone in volcanic geology. Marshall proposed the name "ignimbrite" to include a large group of rhyolitic rocks that cover approximately 10,000 square miles of the North Island and that he regarded as formed by an eruptive process similar to that proposed by Fenner for the sand flow of the Valley of Ten Thousand Smokes.

One of Marshall's greatest contributions was his correlation of field studies with petrographic studies. He noted welding in tuffs as observed by Iddings and he was the first to recognize the importance of devitrification in obscuring the fragmental character of these glassy pyroclastic rocks (fig. 97).

Richards and Bryan (1934) in discussing the origin of the Brisbane tuff (fig. 75) of Queensland, South Australia conclude that

> * * * the combination of tuffaceous and non-tuffaceous characters presented by the Massive Tuff could be most readily explained as due to an enormous eruption of the incandescent avalanche type * * *

and that

> The Massive Type of the Brisbane Tuff presents many features closely analogous with those of the Ignimbrites of New Zealand and has also much in common with the Hot Sand Flow of Alaska.

As did Marshall, these writers related petrographic to field characteristics and recognized materials closely resembling the welded pumice of Iddings.

At about the same time and without knowledge of the work being done in New Zealand and Australia, Mansfield and Ross (1935) described a group of rocks from southeastern Idaho for which they used the term "welded tuff" (figs. 9, 10, 17, 18, 49–54, 61, 70). These tuffs were compared to the "welded pumice" of Iddings and are possibly related to the vast fields of Yellowstone rhyolite, much of which is now known to be welded tuff. These writers concluded that the Idaho tuffs have many features in common with the Katmai sand flow and may have had a similar origin.

The integration of field studies with petrographic studies, as in the works of Marshall, Richards and Bryan, and Mansfield and Ross, established a direct relation between welding in pyroclastic materials and an origin of some of these materials from a particular type of volcanic eruption. It provided a correlation between some of the welded pumice of Iddings and volcanic eruptions of a type exemplified by Pelée, Soufrière, and the Valley of Ten Thousand Smokes. This relation seems true although no welding was observed in the deposits at Pelée, Soufrière, or at Katmai by the early workers there. The present authors have examined material from Katmai and have found evidence of slight plasticity and possibly very slight local welding of some of the shard fragments.

Although in 1935 there was much yet to be learned about welded and nonwelded ash-flow tuffs, the outstanding features of these rocks had been presented in the above discussed papers on the New Zealand ignimbrites, the Brisbane tuff, and the welded tuffs of southeastern Idaho. There followed a series of papers by several authors describing new localities for welded tuffs and presenting detailed studies of tuffs from specific areas.

Fenner (1937) proposed the term "Katmaian type of eruption" to apply to eruptions that formed deposits having the characteristics of the sand flow of the Valley of Ten Thousand Smokes. He suggested that several of the pyroclastic deposits of Yellowstone National Park had such an origin.

Gilbert (1938) described a group of welded tuffs from eastern California. These tuffs comprise the Bishop tuff that covers 400 square miles and has an average thickness of 500 feet. Gilbert's paper is an excellent treatment of the subject of welded tuffs and probably is one of the best in its organization and presentation of the facts, both field and petrographic.

Stearns, Crandall, and Steward (1938) mention welded tuffs in the Snake River Plains area, and the Mud Lake region, Idaho. Anderson and Russell (1939, p. 243–247), in describing the Tertiary formations of northern California, were the first to use a recognized ash-flow deposit as a stratigraphic marker. The "Nomlaki tuff," they believe, has "covered an area of at least 2,000 square miles." This study is valuable as it points out the tremendous potential use of ash-flow tuffs for stratigraphic correlation. Feitler (1940) briefly described glassy welded tuffs from Bare Mountain, Nev. Kuno (1941) discusses the different characteristics of deposits formed by "pumice flows" and those formed by "ejected pumice" as observed in the deposits formed by the eruption of the volcano Komagatake in 1929. He also compares these pumice-flow deposits with Pleistocene and Recent pumice deposits of some of the other Japanese volcanoes and finds that they have very similar features. Ross (1941) found that the well-known "thunder eggs" (chalcedony-filled spherulites) from central Oregon formed in a welded tuff (figs. 67–69).

Williams (1941a) in his excellent paper on calderas discusses welded and nonwelded ash-flow tuffs and their common association with collapse calderas of the Krakatau type. In his study of the geology of Crater Lake National Park, Williams (1942) describes both welded and nonwelded ash-flow tuffs and discusses their origin from "glowing avalanches." Westerveld (1942) describes "welded rhyolitic tuffs" from South Sumatra and discusses their origin, chemistry, and similarity to similar deposits in other parts of the world (figs. 16 and 22).

Matumoto (1943) describes in some detail the so-called Aso lava which forms vast deposits around the Aso caldera. He says, "* * * the name Aso lava was originally given to the obsidian-bearing, piperno-like, agglomeratic, eutaxitic, or welded mud lava found along the top of the somma." In an elaborate classification, he subdivides the Aso lava into several types. The paper is well illustrated with photographs of polished specimens of the Aso lavas and photomicrographs of thin sections (fig. 81). Bonorino (1944) describes andesitic welded tuffs from Argentina (figs. 83 and 84).

Zavaritsky (1946, 1947) adequately explains many hitherto anomalous features of the Armenian "tuff lavas" as compatible in origin with an eruption of Katmai type. Following Fenner's usage, Zavaritsky (1947) classifies as deposits of the Katmai type several of the better known ash-flow deposits. His list includes the New Zealand ignimbrites, Bishop tuff of Gilbert in California, Crater Lake welded tuffs and pumice flows, Japanese "Aso lavas" and the classical Italian piperno. Following a review of the main features of the above-named deposits he describes the principal physical features of the Armenian tuffs and "tuff lavas" (figs. 79 and 80).

Westerveld (1947) concludes that the vast deposits of "acid" volcanic rocks around Lake Toba, Sumatra are welded rhyolitic tuffs (figs. 26, 27, 39, and 65). These rocks cover 20,000 to 30,000 square kilometers, and have an estimated volume of 1,500 to 2,000 cubic kilometers.

Fenner (1948a), in describing the "incandescent tuff flow" deposits in the Arequipa region, southern Peru, concludes that these materials have had an origin similar to the tuff deposit of the Valley of Ten Thousand Smokes, Alaska. The areal extent of these deposits is not known, but Fenner believes that these deposits rank high among the world's greatest known examples of "incandescent tuff." Fenner found that much of this tuff is composed of incoherent constituents and his studies indicated that the indurated varieties were due to recrystallization of shards and pumice fragments and the growth of secondary vapor-phase minerals. He thought that welding was not an important process of induration in these particular rocks (see p. 8, 28 of this report). He thus decided that the term "welded tuff" was not satisfactory as a name for these materials and instead used the locally applied name "sillar" (figs. 24 and 25).

Boyd and Kennedy (1951) were the first workers to approach the problem of welding in tuffs from a purely experimental standpoint. They found that by heating pulverized volcanic glass in a bomb they could effect welding. From this they reached conclusions as to the temperature of formation of welded tuffs (see p. 42 of this report).

Other noteworthy occurrences of welded tuffs that have been described or briefly mentioned in the literature in recent years are as follows:

Recent descriptions of welded tuffs

Location	*Reference*
United States:	
Little Hatchet Mountains, N.Mex.	Lasky (1947).

Recent descriptions of welded tuffs—Continued

Location	*Reference*
United States—Continued	
Iron Springs district, Utah [1]	Mackin and Nelson (1950); Mackin (1952).
Rattlesnake formation, Oregon [2]	Wilkinson (1950).
Lewis and Clark County, Mont	Barksdale (1951).
Sierra Nevada, Calif	Hudson (1951).
Yellowstone National Park, Wyo	Boyd (1954).
Lake Valley quadrangle, southwestern New Mexico	Jicha (1954).
Blake Range, New Mexico	Kuellmer (1954).
Chiricahua Mountains, Ariz	Enlows (1955).
Basement rocks of Texas and southeastern New Mexico	Flawn (1956).
Dragoon Mountains, Ariz	Gilluly (1956).
Other countries:	
Near Parral, Chihuahua, Mexico	Wilson and Rocha (1948).
Baja California, Mexico	Wilson and Veytia (1949).
Islands of the Gulf of California and neighboring land areas, Mexico	Anderson (1950).
Hunter-Karuah district, New South Wales	Osborne (1950).
Sikhote-alin Mountains, eastern Siberia	Solovev (1950).
Costa Rica [3]	Williams (1952).
Eastern Iceland [4]	Dearnly (1954); Tryggvason and White (1955).
English Lake district, northern England	Oliver (1954).
Balsam Chain, Salvador	Weyl (1954).
Precambrian of southern Morocco [5]	Bouladon and Jouravsky (1954, 1955).
Asia Minor	Westerveld (1955).
Salvador	Williams and Meyer-Abich (1955).
Northern Japan	Ishikawa and Minato (1955); Yagi (1956).
Corsica	Bodenhausen.
Oita Prefecture, Japan	Ishii and others (1956).
Peru	Jenks and Goldich (1956).
Japan	Matumoto and others (1956).
Sudbury, Canada	Thompson and Williams (1956).
Precambrian of Sweden [6]	Hjelmqvist (1956).

HISTORIC ERUPTIONS OF ASH-FLOW TUFFS

A study of the mechanisms that produce ash-flow tuffs must begin with the available records of direct observations of volcanic eruptions. These eruptions are rare and minor events compared with those in some earlier geologic periods, however, such eruptions assume great importance, and the following section will present some of the conclusions of the few geologists who have had the good fortune to make direct observations.

PELÉE

The great eruption at Pelée on May 8, 1902, on the Island of Martinique, is recognized as having initiated an understanding of nuées ardentes and the related dispersal of pyroclastic materials. The great initial eruption was not directly observed by volcanologists but a few of them promptly began investigations and gathered valuable information from residents, and the long continued observations on later eruptions built up an outstanding fund of information. Anderson and Flett, Lacroix, and Perret are those who contributed most to an understanding of the eruptions at Pelée.

In discussing the factors that give nuées ardentes the properties of flowing, Anderson and Flett (1903, p. 508–509) say,

> As this turbulent mixture of expanding gases and fine dust pours down the surface of the mountain, the small solid grains are unable at first to rest on the ground, even when they may have sunk to the base of the cloud, and they are swept up again and borne along till they reach some sheltered hollow or the violence of the expansive force lessens and the turmoil diminishes.
>
> The fundamental question remains to be discussed—what is the source of the energy which drives the cloud along? To this we believe there is only one answer—the motive power is supplied by the weight of the mass. It is in a condition comparable to that of a heavy and mobile fluid which has been elevated by the volcanic forces and poised on the edge of the crater and proceeds to flow downward in obedience to the law of gravitation.

The foregoing interpretation of ash-flow mechanisms is evidently a synthesis of observations of the deposits at Soufrière, and, in particular, the later and lesser eruptions at Pelée.

The nuées ardentes eruptions at Pelée were described in great detail by Lacroix (quoted on p. 6 of this report). Lacroix (1904, p. 354) granted the effect of gravity, but emphasized the great importance of an initial eruption and the violent projection of the debris that resulted from this explosion. The directed effect of the blast was the result of its coming from the base of the incipient

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[1] Illustrated in figures 32, 33, 40, and 41 of this report.
[2] Illustrated in figure 29 of this report.
[3] Illustrated in figures 85 and 86 of this report.
[4] Illustrated in figure 19 of this report.
[5] Illustrated in figure 98 of this report.
[6] Illustrated in figure 78 of this report.

spine, whose influence has been discussed by MacGregor (1952, p. 54).

Continuous observations of eruptions at Pelée were made by Perret from 1929 to 1932, and resulted in valuable contributions to the understanding of volcanism and, in particular, nuées ardentes of which he observed several hundred examples (fig. 2). Perret (1937, p. 22–23) says,

> First of all it should be realized that the horizontal movement, three kilometers in three minutes, is due to an avalanche of an exceedingly dense mass of hot, highly gas-charged and constantly gas emitting, fragmental lava, much of it finely divided, extraordinarily mobile, and practically frictionless, because each particle is separated from its neighbors by a cushion of compressed gas. For this reason too its onward rush is almost noiseless. To the end of its course the 'auto-explosivity' continues * * *.

Elsewhere Perret (1937, p. 87) says,

> At the moment of explosion liquid masses of lava, instead of being hurled high into the air to form bombs are converted more or less completely into ash by the rapid discharge of gas * * *.

VALLEY OF TEN THOUSAND SMOKES

An important advance in our understanding of the eruptive processes that give rise to ash flows, was a result of studies in the Katmai region of Alaska, where the eruptions more nearly resembled the great ones of the past, than did those at Pelée. However, this eruption occurred in June 1912, and the area was first visited by Robert Griggs in 1915; thus no one directly observed the "sand flow" of that eruption. However, significant relations were observable and some of the later phenomena of the eruption were still active.

A series of papers resulting from several successive expeditions to the Katmai region of Alaska, under the auspices of the National Geographic Society, by Griggs, and by Fenner and Zies of the Carnegie Institution of Washington Geophysical Laboratory, constitute outstanding contributions to the understanding of ash flows.

In discussing the relationship Griggs (1922, p. 253–254) says,

> Surrounded as it is by high and rugged mountains, the most striking feature of the conformation of the Valley of Ten Thousand Smokes is the flatness of its floor. One could ride a bicycle for miles along its smooth surface * * *. Altogether it occupies an area of 53 square miles (137 sq km) * * *. The bulk of the deposit is composed of fine fragments, many of them dust-like, but there are included numerous lumps of pumice, which in places make up a considerable fraction of the whole. There is no trace of stratification of the materials, except where they were obviously subject to secondary readjustments after deposition.

In discussing the "sand flow" Fenner (1923, p. 72) says,

> I would, therefore, stress the remarkable character imparted to the dust and gas mixture by a continuous evolution of gas, which must not only have eliminated almost completely the contact friction of the particles, but also have tended to drive them apart somewhat forcibly and caused the mass to spread almost as freely as a true liquid.
>
> Naturally, gravity would act upon a mixture that was undergoing the assumed reactions just as it would act upon a liquid and would direct its course down the slope of the Valley, but the important fact to be emphasized is the manner in which internal friction of the mass was eliminated, and it seems to me that only in some way as that suggested would it be possible for this to be accomplished.

COTOPAXI

Fenner (1923, p. 65) pointed out that although the mechanism of an ash flow was not understood at that time, Wolf has given an excellent description of such a flow in his discussion of an eruption of Cotopaxi, Ecuador.

In the discussion Wolf (1878, p. 131–132) says,

> About 10 o'clock in the morning, while strong subterranean detonations were heard * * * the crater of Cotopaxi boiled over [übersprudelte] with fluid, glowing lava, and this precipitated itself with furious velocity down the declivities of the cone. I chose the words 'boiled over' intentionally, because they indicated best the manner and form in which the effusion of lava occurred in this extraordinary outbreak * * * the mountain as it suddenly came to effervescence [ebullicion] and threw out a 'black mass' smoking and steaming over all parts of the crater edge simultaneously * * *. It is indeed one of the singular features of this eruption that the lava poured out of the crater not in one or several streams, but symmetrically in all directions, over its lowest edge as over its highest points. On that account the floods were so general around the mountain * * *. Very many phenomena indicate that the new lava must have possessed a very high temperature at its exit from the crater and must have been almost as fluid as water. Its expulsion occurred suddenly with a fearful welling-up of the fluid, glowing masses; for only thus is it explicable that in a quarter, or at most, a half an hour, such a fabulous amount of lava was delivered * * * and that it flowed out over the highest crater edges like the foam from a boiling over rice pot.

One of the significant observations by Wolf is the "boiling over like foam." Not knowing the identity or fluidity of an ash flow, Wolf believed that excessively high temperature was necessary.

SOURCE VENTS FOR ASH-FLOW TUFFS

No eruption of ash flows, that has produced welded tuffs, has ever been directly observed. Thus the nature of volcanic vents that have erupted ash flows in which welding has occurred has long been a subject of speculation. Lacking direct observation, analogy must be drawn among the observed eruptions of nonwelded ash flows, pumice flows, and other types of deposits formed by certain historic outbursts of volcanoes such as Pelée, Soufrière, Komagatake, Merapi, and more recently Lamington and Hibok-Hibok. These are the nuée ardente, Pelean, ladu, glowing avalanche, and other deposits of various writers.

The vents that gave rise to these historic eruptions are immediately divisible into two types, those characterized by open craters, and those superimposed on volcanic domes. Eruptions from domes seem to follow more than one pattern. The specific characteristics and origins of these eruptions have been a subject for controversy, and they have been discussed and classified by several authors: Lacroix (1930), Escher (1933a, b), Kemmerling (1932), Grandjean (1931), MacGregor (1946, 1952), van Bemmelen (1949), and Weyl (1954b).

A lengthy discussion of these differences is not pertinent to the main topic of this report. Briefly, they concern the directed-blast hypothesis of Lacroix, the simple, as well as explosive, avalanching of the sides of the volcanic dome, and eruptions from fissures and subsidiary craters in the dome. These processes all seem to produce the so-called nuée ardente phenomenon, but the pyroclastic products vary greatly in size range and composition. The products of greatest significance to students of ash-flow tuffs are those that consist primarily of new magma. This condition is met in certain eruptions from the domes and, to a greater degree, in eruptions from open craters. Deposits formed from dome eruptions seem to be restricted in volume and distribution, the latter being dependent on the location of the vent or vents. Eruptions from open craters, being less restricted, tend to produce deposits with a more symmetrical distribution around the crater, with probably greater volume and greater areal extent.

As mentioned above, eruptions of both types have been observed and others have taken place in historic time, but in no known instance has either type produced a welded ash-flow tuff. Therefore vents that produced deposits of welded ash-flow tuff remain to be discussed.

Small deposits of welded tuff (covering a few square miles) are probably not uncommon and they may have been derived from vents such as were discussed above. A small deposit of welded rhyolite tuff (less than 10 square miles) in the Valles Mountains, N.Mex., probably came from a small crater that was later filled and covered by a large rhyolite flow. However, a dominant proportion of welded tuffs are found in ash-flow sheets of great areal extent. The great extent and tremendous volume of some of these deposits are incompatible with eruptions from single domes or single craters. A third type of vent, the fissure type, offers an adequate explanation. Fissure vents have been assumed by van Bemmelen (1949), Westerveld (1952), MacGregor (1952), and others.

The field evidence for fissures as a source for ash-flow tuffs is meager and indirect evidence is most suggestive.

Williams (1952, p. 155) states, "There is no way of telling whether the voluminous Costa Rican avalanches issued from the summit vents of Poás and Barba or from fissures on the flanks."

Wilbur Burbank, of the U.S. Geological Survey, believes the rhyolite dikes he studied in the Independence Pass region of Colorado were feeders for the extensive welded tuffs closely associated with them. A suite of these rocks made available by Burbank to the authors was studied, and a thin section cut from one of the dikes is illustrated in figure 37. This shows intricate flow structures sweeping around the abundant phenocrysts. There is no sign of vesiculation or of the collapse of bubble fractures.

Other evidence of the existence of fissure feeders is less direct, but still convincing. This indirect evidence is found in the large collapse structures so commonly associated with extensive pyroclastic deposits, especially ash-flow tuffs. The large size of some of these deposits precludes their origin from a single vent; they were probably erupted from a series of vents or from fissures. The linear characteristics of some of these collapse structures clearly indicate control by regional faults or rift zones and strongly suggest that the ash flows were erupted along these linear zones of weakness.

The relation between voluminous pyroclastic eruptions and certain collapse calderas has been discussed by Williams (1941a) and van Bemmelen (1939, 1949).

Some welded-tuff deposits, especially the more andesitic ones, are traceable to definite volcanic centers, but here their specific point of emission is generally obscured by a collapse caldera. Where the caldera is smaller the eruptions probably came from a single crater, whereas in a larger more complex caldera the eruptions came from a group of craters or fissures, possibly ring fractures. In the

Valles Mountains, N.Mex., the welded tuffs came from an area now occupied by a large caldera 14 miles in diameter. Within this caldera there is a ring of rhyolitic centers about 8 miles in diameter that formed after the caldera. This arrangement of centers within the area of caldera collapse surely represents a ring fracture and the eruptions that produced the welded-tuff deposits may have been localized along the same fracture. A similar origin from a ring dike was postulated for the rhyolitic pyroclastic rocks on the Island of Mull (Richey and Thomas, 1930, p. 370).

In the Western United States and Mexico, especially in the Basin and Range province, there are vast deposits of welded tuffs that have not been correlated with any known centers. These deposits occupy very large areas on the ranges but are covered with immense thicknesses of fill in the intervening trenches, and offer many challenging problems.

RECOGNITION OF ASH-FLOW TUFFS

The recognition of ash-flow tuffs has long presented a difficult problem because of a lack of knowledge concerning their mode of deposition and the reliability and limitations of field and laboratory criteria. As has been discussed on page 13, a real understanding of the geologic relations of these rocks did not come until the early and middle 1930's, resulting from the correlation of field and laboratory studies with information gathered from earlier observations of significant volcanic eruptions. Although more and more geologists are becoming familiar with these rocks, and the actual existence of such rocks is recognized by most geologists, many workers are still confronted with problems of recognition. The discussions in the following pages together with the illustrations may help clarify some, if not most, of these problems.

Nonwelded ash-flow tuffs are often confused with tuffs of other origins and welded tuffs are often confused with lava flows. This is especially true of the devitrified tuffs. The ash flows of a more heterogeneous nature may be confused with lahars and transitions may exist between one and the other. Normal vitric tuffs are sometimes fused in contact with lava flows or shallow intrusions and these may be mistaken for welded ash-flow tuffs.

The following section is divided into two main parts. The first part pertains to field characteristics or those features of ash-flow tuffs readily discernible in the field. The second part is a treatment of microscopic characteristics.

The sections on field characteristics, microscopic characteristics, and the one on physical chemistry must all necessarily involve a certain amount of recapitulation, but an effort has been made to keep this at a minimum.

FIELD CHARACTERISTICS

PYROCLASTIC CHARACTER

The pyroclastic nature of ash-flow tuffs is generally discernible in the field. In unaltered nonwelded tuffs there is no problem because the presence of unconsolidated pumice fragments, ash, volcanic dust, and the ubiquitous foreign rock fragments would indicate pyroclastic origin for any tuff. These features are discernible through milder types of induration and alteration, and become obscure only when advanced stages of welding and devitrification have been reached. However, even in advanced and extreme examples of welding and devitrification a careful search will generally reveal rock fragments which, even if not diagnostic in themselves, should cast doubt on the rock being a lava, and together with other features to be discussed, should give the correct answer.

The most important single criterion for recognition of the pyroclastic nature of ash-flow tuffs in the field seems to be the presence of pumice fragments. These pumice fragments occur in nearly all ash-flow tuffs and commonly persist in some form through extreme conditions of welding and vapor-phase mineralization, and are generally obscured only when extreme devitrification follows extreme welding. In very fine grained tuffs the pumice fragments are too small or too few to be of much aid in field studies and other field or microscopic criteria must be used. A few crystal-rich tuffs also show few pumice fragments. Success in the use of pumice fragments as a criterion for pyroclastic character of a welded tuff depends on a familiarity with the extremely diverse appearance of pumice fragments under different conditions of welding, devitrification, and vapor-phase crystallization. This knowledge comes with the study of many diverse types of welded tuff.

In some localities all the above mentioned conditions may be observed in a single rock outcrop because of varying degrees of compaction, welding and devitrification in different parts of a single ash flow. Where this occurs the relation between seemingly different structures becomes obvious, and their dissimilarities become understandable.

Ash flows of the type exemplified by Battleship Rock in the Valles Mountains, N.Mex., present an opportunity for studying pumice relations under varying conditions of welding and compaction. Here a single sheet is nonwelded at the base and top, whereas a central part shows marked welding. The character of the tuff scarp is shown in figure 3; the highly pumiceous character of a hand specimen from near the base of the unit is shown in figure 42; and a thin section of the same material is shown in figure 43. A hand specimen of a thoroughly welded part of the same unit is shown in figure 1. Here the pumice fragments have completely collapsed, and welding has eliminated much of their internal structure.

Were it not for a complete transition from typical pumice to a material resembling blebs of glass, the origins of the black lenses shown in figure 1 would not be recognizable. The characteristics of pumice that has undergone several modifications are discussed in some detail on page 33. However, nearly all lenticular elements in a welded tuff (unmetamorphosed) that are observable in the hand specimen or the outcrop, probably are, or were, pumice fragments. The one exception to this is in those rare welded tuffs that have developed lithophysae. Most lithophysae are nearly spherical, but a few may be flattened and thus appear lenticular in cross section.

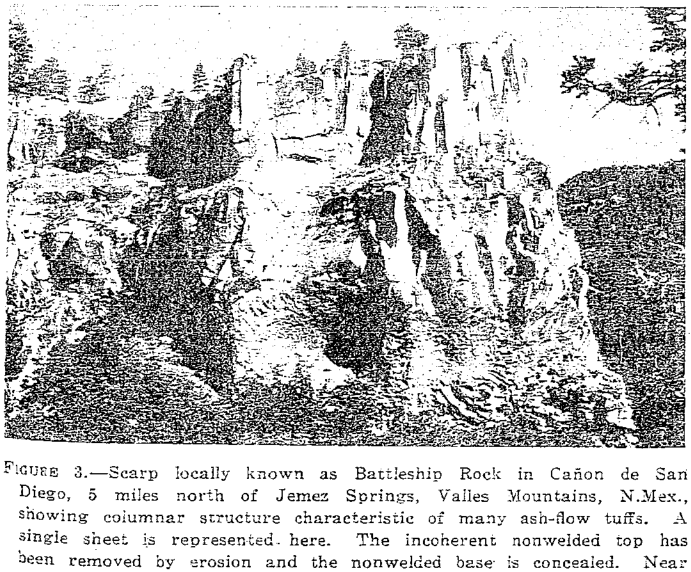

FIGURE 3.—Scarp locally known as Battleship Rock in Cañon de San Diego, 5 miles north of Jemez Springs, Valles Mountains, N.Mex., showing columnar structure characteristic of many ash-flow tuffs. A single sheet is represented here. The incoherent nonwelded top has been removed by erosion and the nonwelded base is concealed. Near the lowest visible part of the scarp (about one-third above the base) is a zone of maximum welding. The erratic jointing near the base was probably due to uncommon cooling conditions as this material descended a canyon, whose wall was not far to the left and so presented a lateral cooling surface. Material from the nonwelded base of this unit is illustrated in figure 42, and the thoroughly welded central part in figure 1.

DEGREE OF SORTING

A principal characteristic of ash-flow tuffs is their common occurrence in thick units (tens of feet) of typically nonsorted or nonbedded materials. This characteristic is in direct contrast to ash-fall tuff deposits of comparable thickness, in which pronounced bedding is nearly always present, as shown in figure 4.

Ash-flow tuffs commonly show a wide range in size and relative amounts of constituent materials. However, the dominant material is generally ash or fine ash size (<4 mm) although some types are composed predominantly of pumice lapilli or blocks of different sizes, and for these the term "pumice flow" may be more suitable than ash flow. Dust or fine ash-size material is nearly always present. All gradations exist between those deposits that consist primarily of ash and dust and those that are predominantly pumice lapilli or blocks, although the ash-size types seem to be the most common. Included accidental rock fragments, that commonly add to the heterogeneous appearance of the ash-flow tuffs, may range from microscopic size to large boulders, but are most often 1 inch or less in diameter. They are generally present in amounts less than 5 percent of the whole, but the authors have observed as much as 20 percent in some ash-flow tuffs and this figure is probably much less than the maximum amount.

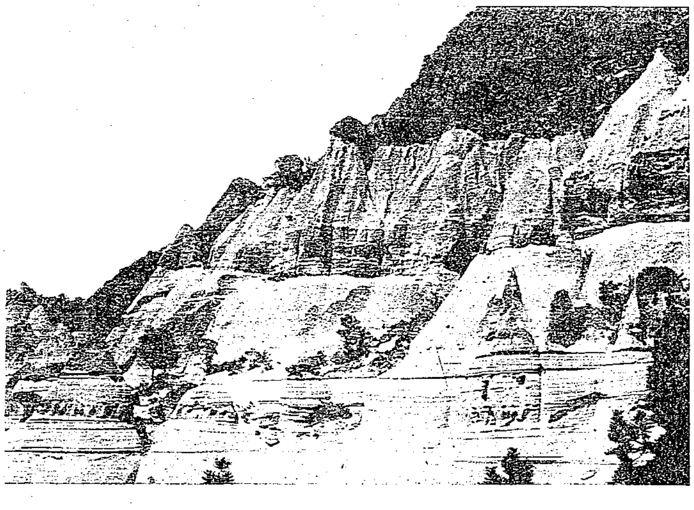

FIGURE 4.—Tuff section on the eastern wall of Colle Cañon, near its junction with Peralta Canyon, Valles Mountains, N.Mex. The lower part of the section is composed of material with the distinct bedding characteristic of ash-fall tuffs. In the ash-flow materials above this bedding is absent. The tendency for poorly welded or nonwelded tuffs to form conical erosion forms is shown in the light-colored ash flows. The dark-colored material above is also part of an ash flow.

THICKNESS

Some ash flows are only a few feet thick, but in general they are many feet thick. Thus Macdonald and Alcaraz (1956, p. 174–175), in discussing the 1951 eruptions of Hibok-Hibok, Philippine Islands, state that the avalanche materials were 100 to 150 feet thick on the higher slopes of the mountain, but thinned toward the coast, and at Baylao had an average thickness of "60 centimeters." In the Valles Mountains, N.Mex., single flows range from a few feet to 300 feet or more in thickness. Ash flows shown in figures 5 and 6 range from 50 to 200 feet in thickness.

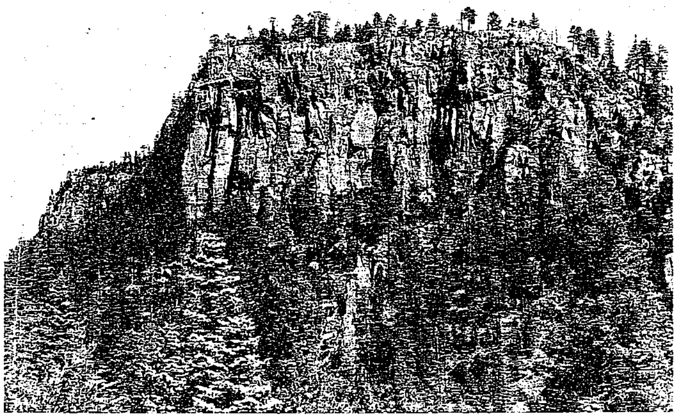

FIGURE 5.—Welded-tuff scarp in Cañon Media Dia, Valles Mountains, N.Mex., showing columnar jointing in thoroughly welded tuffs. The visible part of the scarp represents the densely welded part of an ash-flow unit about 300 feet thick. Unexposed parts, less thoroughly welded at the base, would add nearly 150 feet. Note level top.

FIGURE 6.—Ash-flow tuff scarp below the Puye Pueblo ruins, Valles Mountains, N.Mex. The lower bench represents the thoroughly welded part of an ash flow; the debris-covered slope below represents the poorly welded or nonwelded part of the same flow. The upper cliff is the welded part of a later ash flow, and below it another poorly welded part of that flow. Columnar jointing near the top and middle of the section.

Gilbert (1938, p. 1849) states, "In this section, the Bishop tuff is composed of several members. Some are less than 100 feet in thickness, while others reach nearly 200 feet in thickness." In discussing the thickness of the tuff deposit in the Valley of Ten Thousand Smokes, Fenner (1923, p. 33) says, "* * * it seems indeed quite probable that in the upper valley the tuff may attain a depth of several hundred feet in places." The base is nowhere exposed in this area. Marshall (1935, p. 6) finds that the New Zealand ignimbrites range from about 60 to about 500 feet in thickness, but states, "* * * in general it appears that formations of the ignimbrites are not often thicker than 100 feet." Of those welded-tuff deposits visited by the authors, single units 200 to 300 feet thick are common and units 500 feet thick are probably not rare. In Yellowstone National Park, and the San Juan Mountains of Colorado, greater thicknesses can be found. The thickness of an ash flow depends on the volume of material erupted and the type of topography over which it is emplaced; over gentle surfaces it will tend to spread laterally and form thinner units. If confined to canyons they will flow farther from the source than those flowing over a plain or plateau. If confined to a topographic basin the ash flows will no doubt be thicker. The foregoing statements assume that the initial volume is the same in each situation. There is no reason to doubt that units more than 1,000 feet thick may be found.

LAYERING

Different zones of single flow units have commonly undergone various degrees of consolidation, some parts remaining unconsolidated, others slightly or thoroughly welded. Columnar structures have formed in some zones and very often these zones show different colors or different shades of the same color, with shades of brown and gray occurring most frequently. These features tend to give a layered appearance to many ash-flow tuff units, which is commonly mistaken for the bedding of several flows. This effect of "layering" is further accentuated by weathering in fresh rocks and, no doubt, by metamorphism in older rocks. Many tuffs show a case-hardening effect on the surface, due no doubt to the release of silica from the ash and its redeposition as opal or chalcedony by evaporation at the surface. This thin siliceous coating, having erratic distribution, causes inequalities in the erosion patterns, especially in the nonwelded parts of the ash flows. These are vulnerable to wind erosion that pockmarks their surfaces, commonly with deep holes. These pitted nonwelded tuffs contrast sharply with the more firmly welded parts that react differently to wind and other erosive agents. The net effect is to increase the illusion of layering.

In many ash flows, especially those in which the welded zone is in the central part of the flow, the transition from soft rock to hard rock commonly results in the formation of benches or ledges along this zone. These benches are often covered with rubble that accumulates from falling blocks. The harder zone commonly forms vertical cliffs because it has developed a more systematic pattern of prismatic joints than the softer underlying material, as shown in figure 6. Also, these softer zones may support vegetation; thus it is easily seen why these contrasting types of material have been mistaken for separate flow units and even separate rock types. They commonly have a different mineralogy, color, texture, joint pattern, and erosion pattern; in short, they look different and are so interpreted. The transition zone may be surprisingly narrow and only a careful examination reveals that it really is a transition and not a contact.

In the immediate vicinity of volcanic vents some ash- and pumice-fall tuffs and breccias may tend to form thick beds of a heterogeneous or nonsorted nature, and these may be confused with tuffs of ash-flow origin. However, if it is possible to trace these beds laterally from their vents, their true nature will become manifest with the gradual appearance of graded bedding. The distance from the vent at which bedding will appear will depend on many factors and so it is not possible to give an arbitrary figure. However, within the limits of the authors' experience, bedding will be clearly shown within a few miles from a vent and more often much closer. Ash-flow tuffs have rarely been traced directly to a specific vent so that only under uncommon circumstances should vent tuffs be confused with them.

Volcanic mudflows (lahars) and ash flows have not always been distinguished. However, lahars are typically nonsorted, but tend to be more heterogeneous in composition. They commonly contain a high percentage of rock fragments of boulder and cobble size and, although they may be emplaced in a hot condition, they rarely show any lasting effects of heat. On the contrary, ash-flow tuffs commonly show some indication of having been hot, such as devitrification, vapor-phase minerals, or welding and compaction of pumice shards.

In general, ash-flow tuffs occur typically without bedding within a single flow unit. However, as in all other geological phenomena there are exceptions to the rule. Many ash-flow units are underlain by ash- or pumice-fall beds. Normally there is a clear contact between the fall tuffs and the flow tuffs, but in others the fall and the flow are transitional (fig. 4). The bedding in the ash or pumice becomes more and more obscure upward until it merges imperceptibly with the nonsorted flow tuff above. Probably the best explanation for this gradual transition is that the nonsorted tuff immediately above and transitional with the bedded tuff is also ash-fall material that was deposited in such large volume by eruptions of increasing intensity that gravity sorting was inhibited. The ash fall was then followed by ash flows of the same composition and the contacts between the nonsorted fall tuff and the flow tuff are not discernible. Where unconsolidated material is overridden by an ash flow, there may be an incorporation of ash-fall material in the ash flow.

Some ash flows incorporate rubble of different sorts from the terrain over which they travel. This material, especially when large boulders are present, may be concentrated in lenses or linear zones within the ash flow. These are commonly near the base, but may occur well up in the flow and give an impression of bedding.

A real sorting can take place near the distal ends of ash flows and this commonly results in the partial separation of pumice fragments and blocks. The coarser pumice seems to concentrate on the tops, bottoms, and sides of flow units. In the Valles Mountains, alternating layers, in single flow units, of thin pumice zones and typical nonsorted ash-flow tuff have been attributed to the overlapping of lobes or surges of an ash flow near its distal end. The entire flow near the end of its course was probably separating pumice and perhaps crystals. Thus lobes of the flow, having top and bottom concentrations of pumice and overriding one another, would leave a final product showing a distinct bedding. This bedding is traceable in some localities for several miles back from the ends of the flows and gradually merges with typical nonsorted ash flows.

Probably a great many ash flows would show these features. However, as the ends of the flows are in general thinner and have lost more heat during emplacement than have the thicker parts of the ash sheet, they show less intense welding and vapor-phase crystallization or none at all and are more readily eroded, and thus are less often preserved in older deposits.

A significant paper on sorting during flowage is by Kuno (1941) who contrasts the distinctive features of "pumice flow" and "ejected pumice" deposits, especially those formed by the 1929 eruptions of Komagatake, Hokkaido, Japan. These "pumice flow" deposits show a definite lenticular banding caused by accumulations of larger pumice fragments into longitudinal ridges at the tops of, and within the flows, and formed parallel to the direction of flow. Kuno (1941, p. 147) attributes these to "* * * differential movements of a number of streams within each pumice flow, overlapping one another or merging the one into the other." He further states, "Obviously, the differential movements are the result of differences in the grain-size of the components that formed the pumice flows."

The pumice flows of Komagatake described by Kuno are small compared to many prehistoric ash flows. The Osidasi-zawa pumice flow ends 4 kilometers from the crater and reaches a maximum thickness of only 4 meters. However, these pumice flows illustrate a process that could well be expected in any pyroclastic deposit of similar origin. Any differences would be of degree rather than kind and would depend on the expectable variables of size range, thickness of flow, terrain, distance from source, speed of flow, and probably others.

Another form of overlapping of parts of the same ash flow may take place in terrains characterized by canyons. Ash erupted from a high mountain source may flow down adjoining canyons of different lengths. The flow traveling down the shorter canyon reaches its destination first and is overridden minutes later by the flow in the longer canyon. This process can give a compound effect in the final product and may make proper interpretation of the welding and vapor-phase crystallization processes difficult. Such a process can be demonstrated in the Valles Mountains and is probably not uncommon where ash flows have been erupted in mountainous regions where the valleys or canyons open on a common plain or plateau.

In many ash flows probably some lateral sorting occurs, although there is generally no apparent variation except thinning over long distances. In some deposits the size of shard and pumice fragments decreases away from the source area, but this is less conspicuous than might be expected. The lessening momentum of an ash flow near its distal end may result in a greater accumulation of foreign materials near the base. Similarly crystals may concentrate near the base of units; this process has been suggested by some writers to explain crystal accumulations at the base of some ash-flow tuffs. An alternate explanation for some basal accumulation of crystals is well illustrated by an occurrence of tuffs in Media Dia Canyon in the southwestern slopes of the Valles Mountains, N.Mex. Here in an 800-foot section of ash flows, one flow has a nonwelded base and overlies another flow from which a nonwelded top has been stripped (locally) by erosion. Several feet of tuff, showing a heavy concentration of crystals in a matrix of ash and pumice, occurs at the base of the upper flow. This mixture of crystals, ash and pumice, contains pumice typical of the upper flow and crystals derived from the underlying flow as is clearly shown by the presence of large quantities of chatoyant sanidine crystals which do not occur in the upper flow but are characteristic of the lower flow. Weathering of the tuffs in the Valles Mountains commonly produces a pavement of crystal fragments on the tops of the exposed surfaces. These accumulations have locally been incorporated in subsequent ash flows. The contact between 2 ash-flow tuff units is not always easily discernible, especially if the materials of the 2 flows are similar. In the specific occurrence described above the disconformity was marked by several angular blocks of dense welded tuff that were clearly derived from the underlying unit and, no doubt, littered the surface of that unit prior to the deposition of the upper ash flow. Without these blocks to mark it, the contact could easily have been missed even with good exposures. This would have been especially true had the base of the upper unit been welded. Comparable examples must be very common in many occurrences of ash-flow tuff.

AREAL EXTENT

The areal extent of an ash-flow unit depends primarily on the volume of ash erupted and type of terrain over which it is emplaced. Many workers engaged in the study of welded tuffs have described their great lateral extent. In some of these areas the lack of detailed examination has failed to show whether similarity of character represents wide extent of groups of flows or of single flows. Some ash flows, however, have distinctive characteristics which make it possible to identify single flows that have spread for long distances. In the Valles Mountains a single flow characterized by uncommonly complete welding and abundant chatoyant sanidine feldspar phenocrysts is traceable for about 15 miles west from the eruptive center. In the same region other flows are known to have traveled at least 20 miles from the center of eruption. Griggs (1922, p. 253), and Fenner (1937, p. 236) described the "sand flow" of the Valley of Ten Thousand Smokes as extending for 14 miles with a slope of 2 to 3 percent. According to Williams (1942) pumice flows from Mount Mazama reached a maximum distance of 35 miles from their source. Matumoto (1943, p. 4) states that the so-called Aso lava extends as far as 100 kilometers (62 miles) from the center of Aso caldera.

Anderson and Russell (1939) have traced the Nomlaki tuff member of the Tuscan formation for a distance of about 50 miles. The Nomlaki tuff member is partly welded over a large part of this distance, which has allowed correlation of the Tertiary sedimentary section across the northern part of the Sacramento Valley in California. This study is very significant in pointing out the usefulness of ash-flow tuffs in the correlation of geologic sections. These distances are probably not excessive for ash and pumice flows, and may be exceeded when some of the world's great ash-flow sheets are studied in detail.

Less is known about the maximum areal distribution of single ash-flow units, but the quaquaversal distribution around a crater or along a fissure, of material from a single eruption could conceivably cover several thousand square miles.

The large ash-flow sheet deposits, such as those of New Zealand, Sumatra, Asia Minor, and others, cover thousands of square miles and are made up of many flows from different centers and different eruptions.

The uniformity of these tuff sheets over large areas and distances is an important criterion for their recognition. This uniformity in both welded and nonwelded types is not to be found in either ash-fall tuffs or flow rocks of silicic composition and are rarely found in flow rocks of intermediate types.

GENTLE DIPS

Ash flows tend to have very even upper surfaces and very low angles of dip except where deformation has modified their original attitude. When erupted upon uneven topography the ash flows show evidence of having flowed around obstacles and down drainage channels. They may therefore have a very uneven base and nearly level top in contrast to the blanketing of topography as with ash-fall tuffs (fig. 7). Neither do normal ash-flow tuffs show steep primary dips such as exhibited by many lava flows.

The very even surface of the "sand flow" of the Valley of Ten Thousand Smokes has been described and illustrated by Griggs (1922, p. 257). He remarks that a bicycle could have been ridden over much of the surface. In discussing the New Zealand ignimbrites Marshall (1935, p. 4) states, "Physiographically it may be said that within this district the outcrops of the ignimbrite rocks can generally be recognized in the field, even before they are closely approached. Usually they have a surface that is approximately level; * * *." The even upper surface of ash flows has also been described by Gilbert (1938, p. 1837) for the Bishop tuff of California, and by Zavaritsky (1947, p. 11) for ash flows of Russian Armenia. They are well shown by the Crater Lake "pumice and scoria" flows and by the ash-flow tuff deposits of the Valles Mountains, N.Mex. (figs. 6 and 8). The nearly level tops have also been observed by the authors in other parts of New Mexico, Arizona, Utah, Nevada, Colorado, Oregon, and Wyoming.

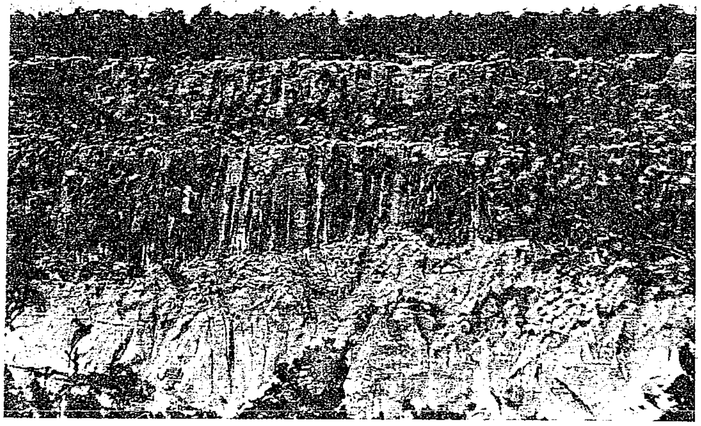

FIGURE 7.—Ash-flow tuff scarp of Capulin Canyon, Valles Mountains, N.Mex. Three ash flow units are shown in this figure, the upper two are welded tuffs, and the lower light-colored one is a nonwelded tuff. The columnar structure commonly developed in welded tuffs is well shown in the two upper beds. The level surface is characteristic of the top of an ash flow.

In deformed rocks an evenness of surface may be reflected in the continuity of outcrop over long distances or persistent recurrence of the same bed in fault blocks. This even upper surface is complementary to the lack of a scoriaceous surface that Marshall (1935, p. 7) cites as an important differ-

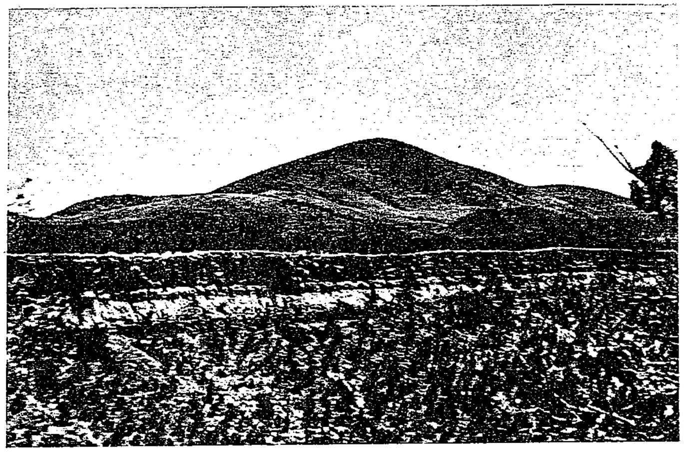

FIGURE 8.—Ash-flow tuff scarp, Valles Mountains, N.Mex.; illustrates the level surface of an ash flow and even bedding in a series of ash flows. The dark upper part is thoroughly welded. The light-colored part is nonwelded. The peak in the background is a quartz latite volcano, formed before deposition of the tuff.

ence between the New Zealand ignimbrites and true rhyolitic lava flows.

WELDING AND DEFORMATION OF PUMICE

Many ash flows contain a zone of welding which is easily distinguished in the field. With others it may be very difficult or impossible to detect welding from field examination alone. The boundary between welded and nonwelded material is always a transitional zone of indeterminate character and the point at which incipient welding begins cannot be located with any high degree of accuracy, even though the transition may be only a few feet thick. The welded zone may occur at the base of the flow or occupy a zone within the flow unit and show transitions above and below into unconsolidated nonwelded tuffs. The position of the zone of welding depends on several factors that are discussed on page 47. All ash flows that completed their cooling history without burial by other ash flows, or other materials, probably had nonwelded tops which may or may not have been removed by erosion. However, in some areas the emplacement of flows in rapid succession results in a complex of flows welded in their entirety, especially near the source areas.

Compaction and flattening of the glassy components normally accompanies welding, although specimens obtained in the transition zones from welded to nonwelded material may at times show a high degree of welding without obvious deformation of the glassy parts (fig. 28).

The most striking field characteristic that marks the transition from nonwelded to welded material is the change in appearance of the pumice fragments. Welding and compaction together, without devitrification and vapor-phase crystallization, cause the pumice to change in shape and color. Fresh glassy pumice normally ranges from white or gray to some shade of brown, depending on its chemical composition. However, during flattening and welding the pumice darkens until in the strongly welded zones it becomes black and obsidianlike. These black glass lenses have heretofore been commonly mistaken for, and referred to as "clots" or "shreds" or "pasty glass fragments." They are the "fiamme" of the Italian piperno (Zambonini, 1919, p. 66–68; Zavaritsky, 1947, p. 12), and the "obsidian spindles" of the "Aso lavas" (Matumoto, 1943, p. 7). It is this flattening of pumice fragments and other constituents by load compaction that imparts a foliate (eutaxitic) structure to most welded tuffs. Viewed normal to the plane of foliation the collapsed pumice fragments appear as discs or irregularly shaped flattened plates; viewed parallel to the plane of foliation they are lenticular. The difference in the two planes is illustrated in figures 83 and 84.

Extreme conditions of welding may produce a zone of dense obsidianlike glass. This may be homogeneous or it may range into a "porphyritic" glass with a high percentage of crystals or rock fragments, depending on the makeup of the magma at the time of its eruption. Examination with a hand lens of glasses formed by extreme welding will usually reveal their fragmental nature. Even in those rocks with the outward appearance of a normal, nearly black obsidian, the collapsed pumice is commonly a more intense black than the material comprising the groundmass shards. This contrast is heightened by wetting. The welded tuff from southeastern Idaho, illustrated in figure 9, would undoubtedly be mistaken for a normal obsidian. However, where water or oil is applied to a ground or otherwise smooth surface, examination under a low-power lens reveals a fine-grained ghostlike structure that represents dim, but definitely recognizable, slightly flattened lenses a fraction of a millimeter in length. They show a foliation in one plane, but no semblance of a flow structure is revealed. That is, the rock dimly retains a very fine grained fragmental structure that is more clearly revealed by microscopic study (fig. 10).

The welded zones commonly differ in appearance from the nonwelded parts because of differences in color, density, porosity, jointing, and the secondary effects of weathering and erosion. These differences give the appearance of gross bedding within a single flow, and frequently lead to a misinterpretation of the number of flows involved. This is especially true in areas where exposures are poor and the rocks have been deformed. In most of the glassy welded tuffs studied by the authors, welding to a compact glass has not taken place. Instead, the rock has a blotched or streaky appearance due to the contrast in color between the darker collapsed glassy pumice fragments and the lighter matrix of glass shards and crystals (fig. 1). This type of glassy welded tuff is the most common and easiest to recognize. The size of the pumice fragments varies greatly from locality to locality as well as within the same rock specimen.

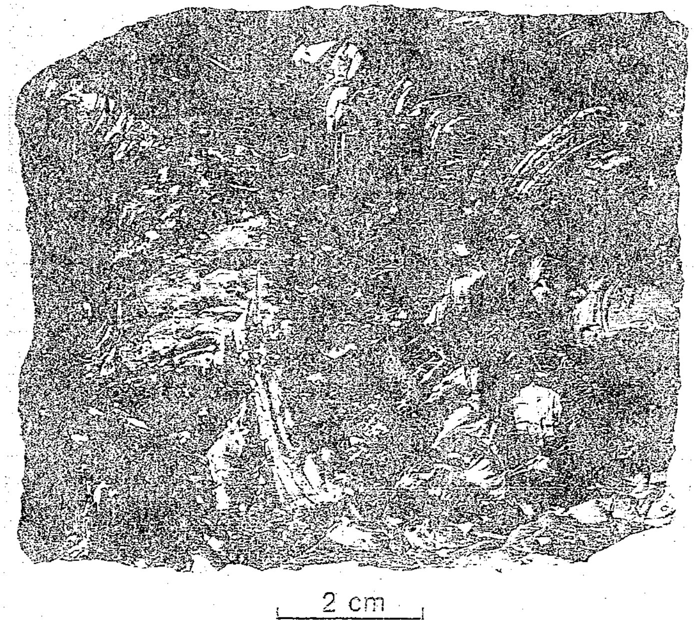

FIGURE 9.—Photograph of a hand specimen of welded tuff with conchoidal fracture, and superficially resembling a typical obsidian. However, a polished or smooth wet surface shows a very fine grained, but recognizable, pyroclastic structure when examined under a low-power microscope. Collected by Ross and Smith from the Ammon quadrangle, southeastern Idaho. × 1.

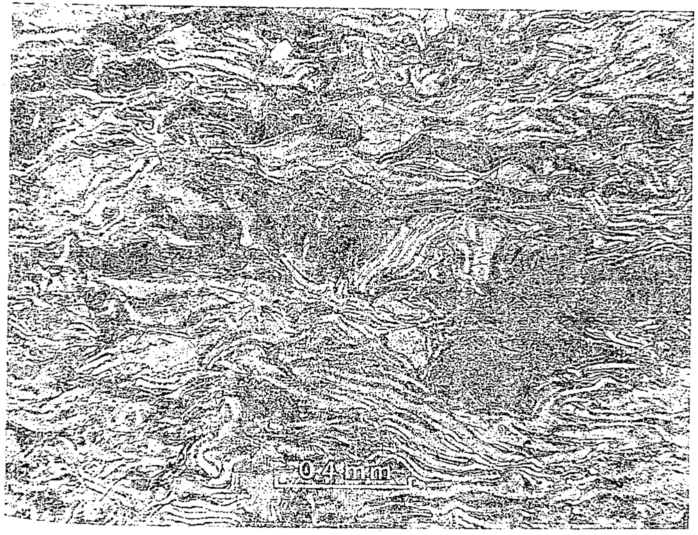

FIGURE 10.—Photomicrograph of thin section of glassy welded tuff illustrated in figure 9. Very complete welding has eliminated all pore space and the different shards are molded one against another with moderate compression. The shard structure is well retained. Compare the distortion with that shown in figure 36.

In most welded tuffs, load compaction and flattening of the shard structure occurs without complete elimination of all pore space, but in some tuffs all pore space has been eliminated, and distortion may stop here, or the pumice and more rarely the shards, may be further squeezed and distorted. When this happens the pumice and fragments will show as greatly flattened and enlarged discs in the plane of foliation and as greatly elongated lenses in the other plane. The result is a disc or plate with a vertical dimension many times smaller than the other two dimensions.

Most pumice fragments have primary shapes that range from those that are virtually equidimensional to those that may have their short dimension 2 or 3 times smaller than their long dimension. During emplacement of the ash flow there will be a tendency for the pumice lapilli or blocks to orient with their short dimensions in the vertical plane. These pumice fragments may be compressed and pore space eliminated during welding by a reduction of vertical dimensions of as much as an order of 2 to 6 times. Deformation during welding added to an original flat shape may give an end product that will have a vertical dimension perhaps 3 to 20 times smaller than the dimensions in the horizontal plane. Collapsed pumice fragments having a discordance in dimension of this order should be considered normal and are probably the result of simple elimination of pore space. However, some welded tuffs are characterized by pumice fragments that have vertical dimensions ranging from 20 to 60 times smaller than their other dimensions. These pumice fragments have been flattened beyond the point of simple loss of pore space, and there has been a stretching of the structure, which may be mistaken for the flow lines of a lava flow (figs. 40, 41).

The deformation or flattening of pumice will result in a higher concentration of crystals per unit volume in welded zones than in nonwelded zones. In tuffs with a low initial concentration of crystals the difference in apparent content of crystals between nonwelded and welded zones will not be obvious, but in those tuffs whose initial crystal concentration was high the difference may be striking.

The ratio of pumice fragments to shards will have a significant influence on the amount of crystal enrichment per unit volume of tuff in welded zones, because of the difference in porosity between the pumice fragments and packed shards. Thus other factors being equal, the ash flow with the highest volume percentage of pumice will have the highest potential for crystal concentration per unit volume during welding.

Some densely welded tuffs have been found to occur in very thin units of a few feet to a few tens of feet in thickness. No detailed studies of such rocks have been published. Probably some very thin tuffs are products of fusion and are more properly classified with the fused tuffs discussed on page 26. These thin tuffs are sometimes found at the base of a normal welded-tuff unit that has a strongly welded bottom where there was enough heat to cause fusion of a few inches or a few feet of underlying glassy ash or pumice. This material may be either of ash-fall or ash-flow origin. The prime requisite is, of course, fragmented glass. A 2-foot thick bed of this origin has been briefly described by Enlows (1955). This process of fusion of underlying ash could lead, in some instances, to misinterpretation of the structure of an ash-flow tuff deposit. As already discussed some ash-flow units have a truly nonwelded top and bottom with the zone of maximum welding somewhere above the base. Fusion of the top of a nonwelded unit by the overlying welded base of another flow of the same general appearance could produce a zone of dual origin that would appear to be a single flow with a nonwelded top and bottom. This process, together with the added effects of devitrification and vapor-phase activity, could produce some real complications in a sequence of ash-flow tuffs.

A second type of thin welded-tuff unit is of true ash-flow origin; the only reasonable explanation for flows of this type seems to be that they were emplaced at temperatures high enough to induce complete welding without load being an important factor in the elimination of pore space. Some examples of this type of welded tuff form dense obsidianlike glass (fig. 10) without showing the high degree of flattening of shards as is commonly shown in the basal glass of thick welded-ash flows. Other examples develop lithophysae and spherulites in the glass and still others develop gas pockets in pore spaces where welding has not been complete. Examples of the latter type are usually devitrified. The complete lack, or rarity of phenocrysts is a further suggestion of a high temperature of emplacement.

FUSED TUFFS CONTRASTED WITH WELDED TUFFS

Rocks identical with or closely resembling welded tuffs and of the same composition may be formed by fusion under conditions quite different from the process which is known as welding. This fusion may occur: (a) at the contacts between vitric tuff and rhyolitic domes or dikes; (b) in the granulated breccias at the base of rhyolitic flows; and (c) in the brecciated zones in the glassy parts of flows and domes. The first process is common in areas of intense rhyolitic or dacitic volcanism. The second and third are comparatively unimportant and their mode of derivation obvious.

DEVITRIFICATION AND VAPOR-PHASE MINERALS

The postdeposition mineral changes that commonly affect ash-flow tuffs are devitrification and the development of vapor-phase minerals, which are best shown by microscopic studies (p. 36–38).

Devitrification and vapor-phase mineralization are distinct episodes, even though they are related processes in the cooling history of many ash-flow tuffs. The distinction made by the authors is that in devitrification the formation of crystals takes place within the boundaries of the glass shards or glass mass. In vapor-phase crystallization the formation of crystals takes place in open spaces under the influence of a vapor phase.

Devitrification has obliterated the original glassy character in most welded tuffs, but in a few the pumice fragments have been devitrified, while the groundmass shards have remained glassy. Devitrification imposed on zones of intense welding and flattening of the structure results in a rock that closely resembles a flow lava. However, silicic flow rocks nearly always show flow banding. This means that if linear elements (exclusive of horizontal jointing) in unmetamorphosed rock extend over several feet, the rock almost surely is not a welded tuff. An unusual exception is a pumice-block flow or tuff containing large pumice blocks that have undergone extreme flattening and stretching. Even in these exceptional occurrences the linear elements are lens-like without great continuity.

Devitrification as previously defined simply turns pumice fragments into crystalline material, and the pumice structure may be preserved in its entirety. However, the texture of recrystallized pumice fragments is greatly influenced by the degree of welding, or the extent of flattening, as there is a tendency for the pumice vesicle walls to coalesce during welding. The vesicles of the pumice become smaller and fewer and this may result in the complete obliteration of pumice structure. The formation of devitrification or vapor-phase minerals will tend to further obliterate pumice structure and only ghosts of this structure remain. Vapor-phase crystallization occurs in open spaces, and although it may happen in any of the pumice fragments, except where there has been complete collapse, it is most characteristically shown where there has been no collapse (fig. 11). Where vapor-phase crystals form, the pumice structure may be partly, or in some tuffs, wholly destroyed by the growth of discrete crystals and crystal aggregates. These show a coarser texture than the products of devitrification. Vapor-phase crystallization commonly results in cavities that are lined with or contain mesh works of crystals. The cavities may lack direct evidence of derivation from pumice areas, and may be mistaken for the lithophysal cavities and the vapor-phase crystallization common to flow rocks. The presence of vapor-phase minerals in pyroclastic rocks is commonly a good criterion for ash-flow origin. Some ash flows have retained volatiles during welding, and these may build up vapor pressure so that cavities are developed, and in these typical lithophysal minerals will be found.

Spherulites and lithophysae may form in some welded tuffs but they are less common than might be expected, perhaps because flow rocks tend to retain a larger proportion of volatiles than do ash-flow materials. True lithophysae do develop in some localities in great numbers (figs. 49 and 52) where they may so dominate the outcrop that all or nearly all the diagnostic features of the welded tuff as observed in the field may be obliterated.

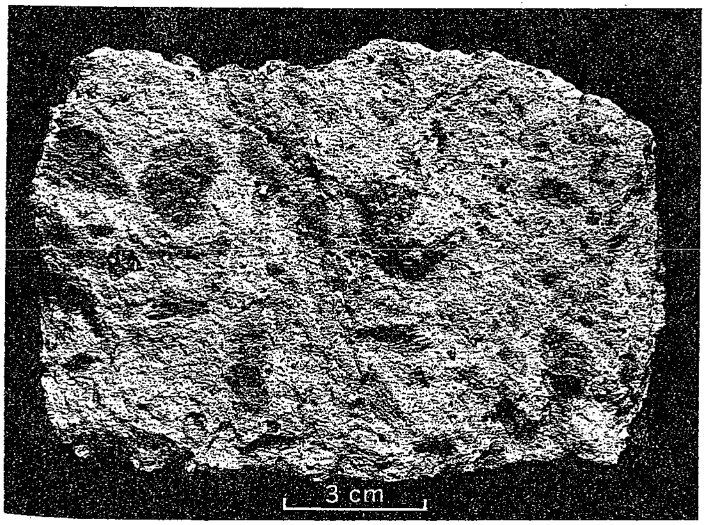

FIGURE 11.—Photograph of ash-flow tuff from 4 miles north of Thumb Ranger Station, Yellowstone National Park, collected by Ross and Smith. The dark areas represent pumice fragments that have devitrified without collapse and in which vapor-phase minerals have formed. Tridymite formed in the cell walls giving them a very fragile texture that is readily broken down by weathering; this gives the tuff a deeply pitted surface. The groundmass is composed of typical shards.

Typical round lithophysae are easily recognized and there should be no question as to origin. Hollow and expanded spherulites appear much the same as they do in normal lava flows and call for no additional discussion. However, in some rare occurrences of welded tuffs, lithophysae become flattened and thus more or less lenticular in cross section and resemble flattened miarolitic pumice fragments. The origin of these cavities may be difficult to determine, especially in older rocks or rocks that have undergone alteration or deformation.

In many welded tuffs where vapor-phase minerals have formed in moderately to strongly flattened pumice fragments, pumice structure is not readily detected in the lenticular cross sections of the flattened pumice fragments. However, if the rock is split in the plane of flattening (foliation) the pumice fragments appear as discs or irregularly shaped plates, and ghost pumice structures are nearly always discernible.

The vapor-phase minerals and minerals formed by devitrification are discussed in detail on pages 36–38. However, some of these minerals may be recognized in hand specimen and outcrop with the aid of a hand lens and so may be briefly mentioned here. The products of devitrification (as used in this report) are preponderantly cristobalite and feldspar and are too fine grained to be recognizable in the field. The main products of vapor-phase crystallization are tridymite, alkalic feldspar, and cristobalite. Cristobalite that occurs as tiny white balls or crystal rosettes and alkalic feldspar predominate in lithophysae, while tridymite and alkalic feldspar predominate in the crystallized pumice and other porous areas of partly welded and nonwelded ash-flow tuffs. When these minerals are found in pyroclastic rocks it is an excellent indication that the rocks were of ash-flow origin. Here again exceptions may be found, but only rarely in such rocks as the fused tuffs that were discussed on page 26 and in other pyroclastic rocks that have undergone vapor-phase alteration originating from sources outside the body of rock in question. Such occurrences are not common and should be readily resolved in the field.

Some ash flows come to rest and remain in an entirely unconsolidated or nonwelded state. Others may, depending on a number of factors, be partly or wholly welded and still remain in a glassy state. Other ash flows may be wholly or partly devitrified and may develop vapor-phase minerals within their porous parts or develop spherulites or lithophysae within their glass zones. Devitrification during cooling is usually accompanied by the formation of vapor-phase minerals in pore spaces in certain zones within the tuff unit.

Sections of ash-flow tuff units that are welded to the base commonly have a basal glass zone. This may grade upward through a densely welded and devitrified zone to a less welded or nonwelded zone that is devitrified and contains vapor-phase minerals. Sections of units that have an unconsolidated base grading upward into a densely welded zone, that in turn grades upward into a nonwelded top, may have 2 zones of vapor-phase minerals, 1 above and 1 below the densely welded zone which may be either completely or partly devitrified. In thick flow units of this type the pumice and shards at the top and bottom of the unit (above and below the upper and lower zones of vapor-phase minerals respectively) may be unaffected by devitrification and vapor-phase activity. In those ash-flow tuffs that have developed two vapor-phase zones the lower zone is normally thinner than the upper. This fact is the result of the vapors having been squeezed out during compaction and welding and which tended to move upward, but were trapped below the densely welded zone and caused alterations similar or identical to those above but within a more restricted area.

Ash flows that have a high volatile content, but without the load or retained heat adequate to cause welding, may still devitrify and develop vapor-phase minerals. Such ash flows produce deposits as described by Fenner (1948a, p. 884) in the Arequipa region, Peru, and which he termed "sillar." Thus we find the sillar-type ash flow forming complete units, or parts of units, that may also contain glassy or devitrified welded zones or both, as well as fresh unaltered pumice and ash. Devitrified densely welded zones in many ash flows will be found to grade laterally into the sillar vapor-phase mineral zone. Examples of this type of transition are very common in the Valles Mountains, N.Mex.

As shown in the foregoing discussion there may be a great deal of variety in individual ash-flow tuff deposits. When weathering, metamorphism, and deformation are superimposed on these rocks their complete history may be exceedingly difficult or impossible to unravel.

JOINTING

Columnar jointing is a common feature of many welded tuffs. It has been described by Marshall (1935, p. 4) in the New Zealand tuffs; by Richards and Bryan (1934, p. 53) in the Brisbane tuff of Queensland, Australia; by Gilbert (1938, p. 1836) as being characteristic of the Bishop tuff of California; by Westerveld (1947, p. 19) in the Lake Toba region of North Sumatra; by Zavaritsky (1947, p. 9) in Russian Armenia, and by several other writers in more recent years. Fenner (1948a, pl. 2) presents an excellent illustration of jointing in the Arequipa region, Peru.

Columnar structures are common and well developed in the welded tuffs and in those parts of ash flows (sillar) indurated by vapor-phase minerals in the Valles Mountains, N.Mex. (figs. 5 and 7). Normally they do not occur in the noncrystalline nonwelded parts of the ash-flow units. No detailed studies of columnar structures in welded tuffs have been published, and there is little or no data on the details of spacing and attitude of joints or size of individual columns. Observations of the authors in the Valles Mountains indicate that joint spacings may range from a few inches to many feet. The more closely spaced joints are usually found in the zones of most intense welding. In any given locality the joints seem in general to be uniformly spaced, although the spacing may vary greatly over several miles of outcrop. Spacing is controlled by several factors such as rate of cooling, thickness, degree of welding, and others.

Vertical jointing represents the conspicuous type, but departures from the vertical are not rare. Some welded tuffs have developed fan jointing, while others have distorted vertical joints that give rise to bent or warped columns. These features are not common and are probably related to local deviations in the cooling surface. Fan jointing has been illustrated by Richards and Bryan (1934, pl. 6, fig. 2) in the Brisbane tuff of Australia. Fan jointing is well shown in the tuff scarp known as Battleship Rock in the Valles Mountains, N.Mex. (fig. 3). The local relations indicate that this tuff was emplaced against canyon walls, and the abnormal plane of cooling resulted in the fanlike group of curved columns.

Bent columns are known from several localities in the Valles Mountains, N.Mex., and in some of these localities their relation to buried topographic highs seems well established, but in other localities their origin has not been definitely determined. Bodenhausen (1955, p. 47, fig. 10) shows an excellent occurrence of nearly horizontal columnar structure on the shore near the Island of Scandola, Corsica.

An interesting type of jointing is represented by an obsidianlike welded tuff from near Taxco, State of Guerrero, Mexico, which has been studied by Carl Fries, Jr. (written communication, 1958), of the U.S. Geological Survey (figs. 12 and 13). This glassy layer is 10 to 20 meters thick and extends at least 10 kilometers. The jointing has produced a large proportion of plates about 1 inch in thickness, and some are as much as 2 feet square.

FIGURE 12.—Photograph of a specimen collected by Carl Fries, Jr., U.S. Geological Survey, from a 10- to 20-meter-thick layer of welded tuff, at km 153 of Taxco Highway, State of Guerrero, Mexico. The photograph shows the obsidianlike character of this glassy welded tuff. At this locality jointing has resulted in a large proportion of platelike slabs that are commonly about 1 inch thick and cover as much as 2 square feet. For this reason the slabs are quarried and widely used in place of tile as flooring material in this part of Mexico. The joint surface is represented in the central part of the surface of this figure; the opposite joint surface is shown in figure 13.

Many welded tuffs show a horizontal platy jointing in or near the zone of maximum compaction. This platy structure is accentuated by weathering and should not be confused with the platy structure that is commonly developed by weathering along the planes of foliation in zones of partial to complete welding and compaction, and where devitrification has furthered the inequalities of hardness inherent in the eutaxitic structure of these rocks. This type of horizontal platy jointing has not been studied in detail but it seems to the authors that it marks the zone of maximum flattening; however, in a few rocks it is best developed a little below that zone. In some welded tuffs the vertical joints do not extend below this zone of horizontal joints. In others they continue downward through the horizontal joints to die out at the top of a nonwelded tuff that forms the base of the unit.

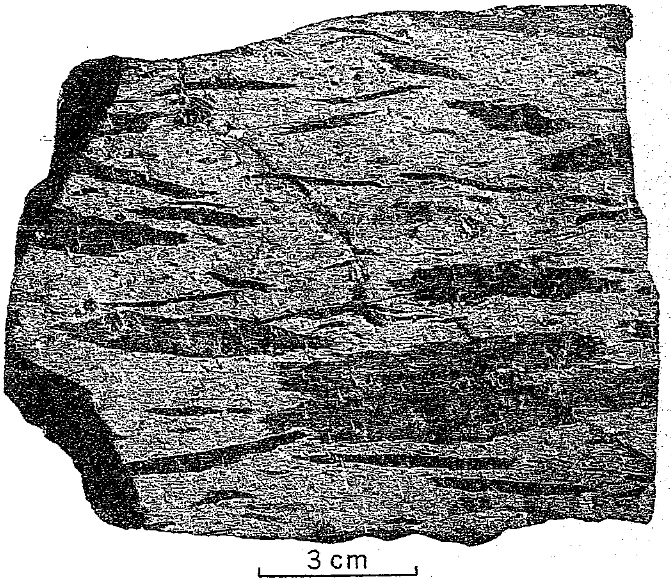

FIGURE 13.—The reverse side of the specimen shown in figure 12 where there has been weathering along a joint crack that has brought out the eutaxitic structure. The lighter colored groundmass shows a fine-grained pryoclastic structure. The darker areas represent completely collapsed pumice fragments. The pumice character is shown by the fraylike ends of many of the pumice areas.

Unlike the joint pattern seen in lava flows that often consists of the well known 5- or 6- (ideally) sided columns, many examples of welded tuffs have columns that are roughly to symmetrically rectangular, and some are square. In general these are tensional cooling joints, but the reason for the wide occurrence of this pattern appearing so commonly in welded tuffs is not clear. It has been observed in many localities in the Western United States, and many illustrations in the literature of welded tuffs from other parts of the world indicate that the joint pattern exists elsewhere. However, Bodenhausen (1955, p. 47, fig. 11) has illustrated columnar jointing in welded tuffs of Corsica that show closely spaced columns, a large proportion of which have 5 or 6 sides.

EROSION FORMS

The wide variations in texture and physical composition, and different degrees of hardness of ash-flow tuffs will obviously produce a diversity of erosion forms. A complete discussion of these would fill many pages and does not seem justified here because of their questionable value as an aid in the recognition of welded tuffs. Locally a specific type of erosion form may aid in the correlation of flows, or may be very diagnostic in distinguishing ash-flow tuffs from rocks of other origins, but each locality must be evaluated by a study of its own peculiarities.

A few specific examples of locally diagnostic forms should be cited. In the Valles Mountains, N.Mex., certain erosion forms are very characteristic and allow recognition of ash-flow tuffs at great distance. Foremost among these are conical shaped pinnacles (figs. 4, 14) that are locally known as tent rocks because of their resemblance to conical tents or tepees. There is a tendency for the formation of these in nearly all the nonwelded parts of the ash-flow tuff deposits but they are particularly outstanding in two members of the Bandelier formation. The Bandelier formation occupies an area of about 400 square miles and at least one of the "tent rock" members is present over most of this area. Some of the "tent rocks" are cones only a few feet high while others are 100 or more feet high (fig. 14). There are all gradations in size and of varying degrees of perfection in symmetry. Some cones are capped by large boulders that were rafted from the ground surface traversed by the ash flow during its emplacement. Some of these boulders weighing as much as several hundred pounds tend to retard erosion and produce boulder-capped pinnacles. Not rarely this results in whole colonies of pinnacles capped by boulders of varying size.

Another diagnostic feature in the Valles Mountains ash-flow tuffs is a magnified "swiss cheese" effect produced by wind erosion. This is common in zones of porous poorly welded tuff (fig. 14) and nonwelded tuff that has been subjected to vapor-phase activity, and to a lesser extent in the unaltered nonwelded zones. In the porous poorly welded zones where vapor-phase minerals have formed these minerals tend to be weakly coherent and thus they are very easily broken and vulnerable to the agents of erosion. This is especially true where these minerals occupy former pumice fragments. Here erosion forms pits that are further enlarged until some reach cavelike proportions. Many outcrops of ash-flow tuffs in the Valles Mountains have casehardened surfaces. Erosion may start at inequalities in these surfaces especially where pumice fragments occur. This gives wind and rain access to the poorly consolidated interior, and conspicuous cavities develop. Some of these cavities were enlarged and used as living quarters by the early Pueblo Indian inhabitants of the region.

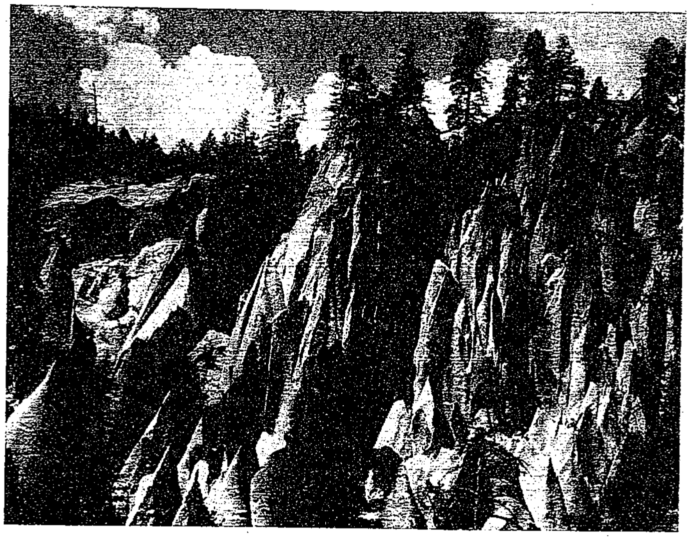

FIGURE 14.—Scarp in Wildcat Canyon, 1½ miles southwest of La Cueva, Valles Mountains, N.Mex. This represents the slightly welded to nonwelded part of a single ash flow, about 400 feet thick. The tuff at the top of the scarp is poorly welded, and an unknown amount of nonwelded tuff has been eroded from the surface. In nonwelded and poorly welded tuffs, erosion localized along vertical joints tends to produce conical pinnacles.

In a recent paper on the welded tuffs of Chiricahua National Monument, Ariz., Enlows (1955, p. 1229) says, "The unusual and spectacular rock formations for which the Monument is famous * * * result from weathering guided by well-developed, vertical joints and the coarse eutaxitic structure." This type of weathering, which is controlled by the foliate or eutaxitic structures of welded tuffs, is well illustrated in Enlows' paper and is mentioned here because it is a common feature of many welded tuffs. Weathered eutaxitic foliation may appear in some welded tuffs like bedding in sedimentary or ash-fall tuffs or like flow banding in some lavas, and may make field determinations of some welded tuffs open to question.

A few hard compact devitrified crystal-rich welded tuffs may superficially resemble intrusive rocks. These welded tuffs are usually dacitic or quartz latitic in composition. One occurrence seen by the authors in southern Nevada contained a large amount of biotite and resembled a granitic rock, even to weathering by exfoliation into rounded knobs typical of exfoliated granite.

FOSSIL FUMAROLES

Williams (1942, p. 86) in his study of the deposits of pumice and scoria flows surrounding Crater Lake, describes features which he concludes are "fossil fumaroles." He says,

> Brown, pink, and white streaks cut the gray scoria where the gases rose to the surface. Some of the spires are hollow inside and have irregular openings at the top. The largest of these tubular spires is 8 feet across * * *. On Sand Creek, as many as 150 'fossil fumaroles' may be counted in a distance of 1½ miles along the canyon walls.

Cementation of the materials surrounding these fumaroles takes place through the deposition of "iron oxides, kaolin, and opal." Erosion of the deposits may leave the indurated fumaroles standing as "spectacular columns and spires."

Similar features have not been reported from any other ancient ash-flow tuff deposit which seems odd. The nature of the ash-flow concept as it is understood at the present time implies that a deposit of this material would give off gases for a long time after its emplacement. Just how long may be seen from Kozu's (1934) study of the pumice flows from the 1929 eruption of Komagatake and from the studies of the sand flow of the Valley of Ten Thousand Smokes. These deposits were still giving off vapors years after they were formed (see p. 41). These gases should leave some trace of their passage through the unconsolidated upper parts of an ash-flow deposit. In the Valles Mountains, N.Mex., the tops of ash-flow deposits are preserved in many localities, but examination of these by the authors has failed to reveal "fossil fumaroles" although some show mottling. The explanation for the apparent absence of fumaroles is not clear. Because nearly all these deposits have a zone which contains vapor-phase minerals it is obvious that the vapors were there. Normally this zone does not extend to the top of the flow unit. The top still contains glassy ash and pumice and is, for the most part, still friable. It is in this part of the flow that the fumaroles should occur. It is all the more peculiar that fumaroles are not apparent in the Valles Mountains deposits when it is considered that the vapor phase was more effective here in converting glass into crystalline materials than in the Crater Lake deposits. There was apparently very little devitrification and growth of vapor-phase minerals in the Crater Lake tuffs. This fact plus lack of welding would indicate a much lower temperature of emplacement and probably a lower volatile content than the Valles Mountains deposits.

Williams found that the signs of fumarolic activity disappeared about 10 miles from the summit of the former Mount Mazama. Thus distance from source might explain the absence of visible signs of fumaroles in other tuff deposits, but this should only be true in those that show no other evidence of vapor-phase activity. Many ash-flow tuff deposits show signs of this activity throughout their entire outcrop area, and this may be 20 miles or more.

Fumaroles in more mafic ash flows should be more colorful because of the higher iron content yielding more iron oxide as a staining or cementing agent. If more colorful they would be more obvious. This might, in part, account for the differences between the Crater Lake flows and the Valles Mountains flows, as the Valles Mountains ash-flow tuffs contain over 20 percent more silica than the "scoria flows" of Crater Lake and about 10 percent more silica than the dacitic pumice flows. Nearly all the Valles Mountains ash-flow tuffs contain less than 2 percent total iron, and some contain less than 1½ percent, while the Crater Lake rocks range from 2½ to more than 7 percent total iron. That is, the iron is inversely proportional to the silica. However, even if iron-oxide coloration was less obvious, fumarolic activity in the tops of the Valles Mountains ash flows should have caused induration because of the release and redeposition of silica and perhaps the development of clay minerals. The only explanation that seems to be left is that the difference in age of the deposits may be great enough to have allowed changes in the appearance of the Valles Mountains ash-flow tuffs, obscuring features that were never too obvious in the first place. This age difference is not very great as the Valles Mountains ash flows were formed in middle or late Pleistocene time and are so fresh in appearance that some of them could not be distinguished in hand specimens from Katmai "sand flow" material.

In summary, the "fossil fumaroles" can be reasonably expected to occur in the upper nonwelded parts of ash-flow tuffs, but they have not been reported from any prehistoric deposits of these rocks except the Crater Lake dacitic pumice and mafic scoria flows. Why they have not been found in relatively young deposits that were certainly potential producers of such features is not clear. It may be that in rhyolitic ash-flow tuffs these fumaroles were never very obvious features and that only very careful scrutiny of prehistoric deposits will reveal their presence, if any trace remains.

MICROSCOPIC CHARACTERISTICS

The field characteristics of ash-flow tuffs have been presented in the preceding section and are usually adequate for identification. The characteristics observable under the microscope are in general also an adequate means of identification, but some ash-flow tuffs are best studied by coordination of both methods. The results of microscopic studies will be presented in this section and coordinated with field studies. Characteristics observable under the microscope also present important information about genetic history and must be considered in connection with the following section on physical chemistry.

The various physical characteristics of ash-flow materials are shown in the illustrations, and discussion in the text will constantly refer to these. However, to minimize so far as possible the need for readers turning from the illustrations to text, detailed descriptions have been prepared to accompany the figures.

Each of the genetic episodes—formation of a glassy magma, vesiculation, eruption, explosive disruption, transportation, emplacement, distortion, degrees of welding, devitrification, and vapor-phase mineralization—have imposed their distinctive effects on the resulting tuffs. The geologist may be called upon to differentiate and evaluate these effects and, so far as possible, to determine the genetic history presented. The following section describes these characteristics in some detail, emphasizes those which seem most significant for purposes of identification, and discusses the situations where ambiguities may arise.

PYROCLASTIC CHARACTER

The origin of both ash-fall and ash-flow materials through the vesiculation and explosive disruption of glass has given these materials physical forms that are not greatly influenced by the chemical differences in the magma from which they are formed. They vary within certain limits in successive eruptions, even from the same centers, but otherwise seem to be basically the same from region to region and have not varied through geologic time. The same shard forms seem to characterize both ash-flow and ash-fall tuffs. However, the subsequent history of these materials is so varied that distinctive differences are developed. The most important of these are the absence of sorting, and the presence of welding and devitrification in ash-flow tuffs.

Tuff fragments vary in physical form, and these may, for convenience, be divided into types, but there are transitions from one type to another. One widely occurring type is derived from a vesiculated glass characterized by roughly globular bubbles as shown in figure 18. This material when explosively disrupted produces curved plates, as shown in figure 16, that represent fragments of the walls of these bubbles; cusp- and lune-shaped fragments as shown in figure 22; and different forms representing the interstitial glass between several bubbles. These may be tricuspidate fragments bounded by arcs of circles, Y-shaped fragments formed in the same way and illustrated in figure 20, and which seem to be one of the most common characteristics of glassy tuff materials. More rarely, forms which represent cross sections of undisrupted spherical bubbles have been observed (figs. 18 and 29). The original plastic glass contained bubbles of different size, shape, and thickness of walls, and so there are many variations to the forms mentioned.

A slight modification of the type of ash derived from globular bubbles was the result of fracture of the walls of elongate bubbles which gave a large proportion of more nearly flat, but commonly slightly curved plates (figs. 17, 20, and 28), among the resulting shards. With these shards are U-shaped or much-elongated Y-shaped forms.

The pumice type ordinarily occurs with other types, and more rarely characterizes an entire occurrence. This material is made up of a fine aggregate of cells that are commonly tubular, but rarely are nearly circular. Pumice tuffs are illustrated in figures 1, 11–13, and 42–48.

During any single eruption the chemical composition of the parent magma and its gas content was about uniform; and at the time of vesiculation, the temperature and the viscosity of the glass varied but little. For these reasons, eruption and vesiculation of the magma tended to produce shards showing marked uniformity during a single episode, except for associated dust and the pumice fragments to be discussed later. On the other hand, successive eruptions even from the same vent may differ greatly in the types of the shards produced.

Some ash flows are made up of nearly uniformly sized shards, as illustrated in figures 28 and 71. More frequently there is a range in dimensions of a hundredfold or more. In other occurrences ash shards are enclosed in a matrix of dustlike materials as illustrated in figures 24 and 25. In some flows this dustlike material is no doubt due to attrition during flowage. However, in some tuffs delicate cusplike shards and bubble walls have not been marred during flowage, even where enclosed in dustlike material as shown in figure 18. The transportation of the shards while enveloped in a film of gas would tend to isolate each shard from its neighbors, and reduce attrition to a minimum. Moreover the shards were at a high temperature, and were still viscous, although viscosity was normally very high. For this reason the hot shards were very much less fragile than they would have been if cold. Rhyolitic glass has such a high viscosity that it may undergo either plastic yield or fracture, depending on the physical conditions.

PUMICE FRAGMENTS

The very common occurrence of pumice fragments as observable in the field has been described in the preceding section but studies under the microscope show the presence of pumice fragments at least of ash size in almost all ash-flow tuffs examined. Some flows are made up dominantly or wholly of pumice, and are best described as pumice flows. The character and modifications of pumice are most clearly observable where it occurs as fragments large enough to be studied in the field, and so conclusions based on field studies need not be repeated here. However, some relations are clarified by microscopic studies and other significant ones are revealed.

The pumice fragments which are normally associated with shard materials, and which they greatly exceed in size, are illustrated in figures 42–48. Most commonly pumice fragments are made up of greatly elongated tubular pore spaces which give the specimen a fibrous structure, but more rarely they are made up of nearly equidimensional roughly spherical bubbles. Very porous pumice fragments are illustrated in figures 42–44.

Pumice fragments in which there has been no collapse are shown in figures 42 and 43. The collapse of the cell structure in glassy pumice is illustrated in figures 45–48, and in figure 13. Crumpling and collapse of pumice lying across the plane of compaction and pumice compressed against phenocrysts are shown in figures 47 and 48. There may also be collapse of the pumice and such thorough rewelding that all internal evidence of pumice structure is lost as illustrated in figure 45. In the hand specimen collapsed pumice may appear as dark blebs of glass as illustrated in figure 1, and which have been discussed in the section on field characteristics.

Pumice may lose its glassy character either by vapor-phase alteration or by devitrification (figs. 55–58). The difference in the significance of these two processes have been discussed on page 44 and their effect on pumice fragments described. The effects of vapor-phase alteration are especially well shown by the field relations. The occurrence of the vapor-phase minerals—feldspar and tridymite—is shown in figure 66.

Pumice fragments are subject to the same devitrification effects as are shards and the resulting minerals—feldspar and cristobalite—are the same. However, pumice fragments tend to be more readily devitrified, and to develop a much coarser grained aggregate of devitrification products than the associated shard materials. In a few specimens the pumice has become devitrified while the shards have remained glassy. The development of the coarse-grained aggregate commonly results in the complete destruction of structure within the pumice as illustrated in figures 57, 58, 61, and 62.

WELDING, DISTORTION, AND STRETCHING

Welding and the accompanying distortion of pyroclastic materials is one of the outstanding characteristics of ash-flow materials. Therefore, the structures formed during welding and criteria for their recognition, even after extreme distortion, present one of the outstanding problems in the study of ash flows. This includes the recognition of the progressive modifications of these structures as a result of increasing distortion.

Welding and distortion can be observed both in the field and under the microscope for many occurrences, but in others can be determined only under the microscope. Even where clearly observable in the field, relations are clarified by microscopic studies.

All ash-flow materials are derived from glassy, vesiculated materials with a wide size range, but in general are dominantly of ash size, and all subsequent changes which these materials may have undergone, have merely been imposed on these primary vesiculated glass structures. However great may be the effect of subsequent changes, they rarely completely obscure the pyroclastic origin of the materials. The genetic history of welded tuffs has given them very definite textural characteristics that are expressed in what has been termed "fabric." Iddings (1909, p. 194) has defined fabric as follows: "The fabric, or pattern, of a rock as shown on a surface or in a section, is that factor of its texture which is dependent on the relative sizes of its component crystals, [or glass fragments] on their shapes and arrangements with respect to one another." This definition, as modified to include glassy materials, effectively outlines the microscopic characteristics which must be considered in a description of welded tuffs.

Welded tuffs usually have a foliate structure (eutaxitic) due to a parallel arrangement of originally flattened plates, or to compaction and flattening of glass shards and pumice fragments into more or less platelike units. The planar arrangement of these platelike units imparts a foliation which has, in many occurrences, been mistaken for lineation due to flowage. Welded tuffs may, however, show a marked lineation resulting from stretching and perhaps very rarely to incipient flowage of the welded, but still plastic material (figs. 40, 41, and 51).

The fabrics developed during welding depend on: the primary form of the shards; the degree of their plasticity—a function of chemical composition and temperature; the compressive stresses acting upon them; and the rate of cooling. Fabric is shown most clearly in the welded tuffs that have remained glassy, but some of the devitrified tuffs also show very well the effects of distortion of the fabric. Varying degrees of distortion are shown in the frontispiece, figures 9, 10, and 24–41.

In some ash-flow materials the shards are in contact with one another only at their points but without observable distortion. Commonly such tuffs have remained glassy, but more rarely even poorly consolidated tuffs have been devitrified as illustrated in figure 17. In some tuffs, especially poorly consolidated ones, it may be difficult to determine whether incipient welding has preceded devitrification. However, many tuffs show marked distortion of the structures that has preceded devitrification as illustrated in figures 51, 59, 60, and 68–70; in these, welding definitely preceded devitrification.

The degree of distortion in welded tuffs ranges from those in which it is slight (figs. 20–29) to those in which flattening and stretching produced a close resemblance to flow rocks (figs. 30, 36, 40, 41, and 59). In many tuffs evidence of distortion may be observed only where the shards are molded against sharp corners of a phenocryst, or where they have been squeezed between two adjacent phenocrysts. In other occurrences there is slight distortion throughout the specimen, and very marked warping around phenocrysts (figs. 31 and 34). Most welded tuffs which have undergone compaction show the greatest distortion perpendicular to the plane of deposition and much less distortion in those cut parallel to that plane, as illustrated in figures 68, 69 and 83 and 84.

With extreme distortion welded tuffs may come to resemble flow rocks. A welded tuff with marked stretching and distortion of the structure is shown in figure 36, and a flow rock with distorted flow lines in figure 37. The two illustrations showed marked similarity, but close comparisons show certain dissimilarities, although these may not be great enough for definitely differentiating them. The discontinuity of the flow lines in the welded tuff (fig. 36), may be contrasted with the more continuous flow lines as shown in figure 37.

In the greatly flattened tuff structures, groups of lines derived from distinct pumice fragments may butt against each other, or meet at an angle. Compressed Y- or U-shaped shards resemble flow lines which have been folded back upon themselves (figs. 51 and 94). Spherical bubbles have been compressed into very flat lenses as shown in figure 40. In some specimens the zones in which the original tuff structure has become obscure will alternate with other zones in which the structure is clearly recognizable.

J. Hoover Mackin studied and brought to the authors' attention the welded tuff from near Iron Springs, southwestern Utah (figs. 40 and 41). The specimen shown in figure 41 has undergone such extreme stretching that it closely resembles a flow rock with lineation. The specimen shown in figure 40 is from the same ash flow, but from a locality where the stretching was not quite as thorough, and the ash structure, although extremely compressed is still discernible. The two are otherwise different in that the specimen represented in figure 41 is glassy whereas that in figure 40 has undergone devitrification.

Solovev (1950, p. 219) in his description of the "ignimbrites" of the Sikhote-alin volcanic region lying between the Amur River and the Sea of Japan, describes stretching of the tuff structures as follows:

> A mass of fragments settled during the movement and the particles—at least a certain portion of them—were compressed because of the high heat and also the pressure from the accumulating overlying pyroclastic material, and were welded in some places, especially in the lower horizons of the column. Such masses, existing in a viscous state, acquired in some localities a fluid character (and could, possibly in some sections even become displaced somewhat to the sides under the weight of the overlying accumulation of fragments). Naturally, this condition could not have failed to be reflected in the structure of the rocks. In a number of places the pyroclastic character of the rocks was more or less completely effaced or even completely destroyed * * * a pyroclastic structure is clearly expressed at a number of points, whereas at other points it does not express itself, or its traces are completely destroyed. In the latter case, the main masses not infrequently acquire a fluid character * * *

all transitions are present, so that these singular rocks have in some places the features of tuffs, and in others the features of lavas.

PHENOCRYSTS AND FOREIGN MATERIALS

Crystalline materials in ash-flow tuffs, other than the devitrification products, are of two types—those which represent phenocrysts which developed as a part of the genetic history of the rocks, and those rock and mineral fragments which are alien to it. Only very rarely have tuffs been observed which were almost free from phenocrysts, and very few which were without at least a few alien inclusions. The proportion of observed phenocrysts ranged from a fraction of 1 percent to nearly 60 percent. The obsidianlike welded tuff from southeastern Idaho illustrated in figures 9 and 10 contained only about 0.1 percent of phenocrysts, and the tuff from McKays, Calif., illustrated in figure 82, is uncommonly rich in phenocrysts. The tuffs from Sumatra (fig. 26) are high in phenocrysts, whereas those from Peru (figs. 24, 25) are low.

The rhyolitic welded tuffs are always characterized by feldspar phenocrysts, and commonly contain quartz. Biotite occurs in small amounts in many rhyolitic tuffs, but becomes abundant in some quartz latite, and rhyodacite tuffs. Magnetite is sparse but rarely, if ever, totally absent. Hornblende is present in a few tuffs. Augite is abundant in some andesitic tuffs, but is more rare in rhyolitic ones. The feldspars of the welded-tuff deposits of the Valles Mountains are almost wholly sanidine, and sanidine that shows a brilliant blue chatoyancy characterizes at least two welded-tuff units. Orthoclase or microcline is rare and where present is no doubt alien, probably being derived from invaded rocks.

The essential feldspar grains are sharply euhedral in outline in a few tuffs, but more commonly they are subhedral. Some show one side with a crystal face, and elsewhere show irregular or fractured edges. Other feldspar grains are rounded or irregularly embayed as shown in figures 19, 34, and 38. In some tuffs, as in most of those from Sumatra, there has been extreme fracturing, so that most of the grains are sharply angular in outline (fig. 26).

Quartz phenocrysts may be sharply euhedral as shown in figure 76, but more often show rounding and embayment as illustrated in figure 31. Anthills are abundant in tuff areas in the Valles Mountains, N.Mex., and in these, quartz grains with lesser amounts of sanidine feldspar are dominant components. The quartz grains are about 2 mm in diameter and are euhedral or partly euhedral in outline and all show evidence of the hexagonal symmetry of high-temperature quartz.

A great variety of materials derived from rocks through which the tuff-forming magmas made their way to the surface, or that were picked up from the surface by the overriding flow, have been observed by the authors in the course of studies of many hundreds of thin sections of welded tuffs from different regions of the world. Alien inclusions are rarely absent and include granite fragments, occasionally fragments of metamorphic rocks, sedimentary rock material, and volcanic minerals and rock fragments that clearly differ in origin from those genetically related to the tuff. Some of these materials also occur as rock fragments large enough to be recognizable in the field or in hand specimens, but those of large size and those observable only under the microscope seem not to differ in character. Most commonly these foreign materials are those of andesitic rocks; andesitic minerals and rock fragments are so ubiquitous in tuffs from the United States and other countries that their absence seems to be a rare exception. Andesitic eruptions have commonly preceded explosive rhyolitic ones, a long-recognized, almost normal geologic sequence, and so an abundance of andesitic materials in welded tuffs is to be expected. In general these rock or mineral fragments are fresh and unaltered. Augite and rare biotite and hornblende are normally perfectly fresh except where subjected to vapor-phase activity. In one specimen examined, olivine in an included basalt fragment was nearly fresh. Very rarely there seems to have been partial fusion of an included fragment, probably representing material picked up at uncommon depths.

Many tuffs show a wide range in the proportion of anorthite in the plagioclase crystals, and the more calcic ones are alien materials. The origin of the alien plagioclase is evidently the same as the commonly associated andesite rock fragments. The more calcic grains have tended to be out of equilibrium with their host rock and suffered alteration or re-solution. Biotite when present may be partly altered with the development of magnetite along its borders. Hornblende may be of a normal greenish color, or not rarely red brown. In some rocks both types of hornblende occur. Another type of alien material represents rock fragments that have been picked up from the surface by the overriding ash flow, and that are conspicuous near the base of some flows. Some of the smaller fragments are observable only under the microscope, but most of them are so large that field studies show their relations best.

DEVITRIFICATION

A large proportion of ash-flow tuffs have undergone devitrification, and this process has been superimposed upon fabric resulting from the welding and distortion of the pyroclastic material. These successive events modify, in many occurrences profoundly, the primary glass shard structures. However, evidence of origin is retained in most devitrified tuffs.

The physical characteristics of devitrified tuffs are closely related to the identity of minerals formed, therefore these will be discussed before further consideration of textures. The slender parallel intergrowths of the devitrification products (axiolitic structures) vary greatly in size, but are normally too fine grained to be identifiable under the microscope. The shards illustrated in figure 28 are marked by light-colored borders which, under crossed nicols, show a very slight grayness, but no resolution of mineral aggregate, even with very high magnification. In nearly all specimens however, the materials are of such a size that under the microscope they have a rough surface, indicating a parallel aggregate of minerals of greatly differing indices of refraction, as shown in figures 71–74, or as in the spherulites illustrated in figures 63–65. The mineral aggregates within the shards can not be definitely identified by means of the microscope. However, many tests of devitrified glass shards and pumice fragments of rhyolitic ash-flow tuffs from many localities have been made by means of X-rays, and these have invariably shown that the products are cristobalite and feldspar.

Before the development of X-ray diffraction methods for the study of very fine grained materials, the identification of minerals of devitrification in volcanic glasses was difficult, or impossible. Fenner (1948a, p. 883) states that small pores between the shards of tuffs from the Valley of Ten Thousand Smokes and from Yellowstone National Park contained tridymite and orthoclase, and that the same secondary minerals occur in tuffs from the Arequipa region of Peru. Fenner's identification of the tridymite in cavities is clearly correct, but he did not specifically consider the devitrification material in dense glass.

Marshall (1935, p. 23, 24) described the development of very slender needlelike structures that develop in glass shards—the material that he called "pectenate" but that Zirkel (1876, p. 173, 174) had previously named axiolites. Marshall also recognized feebly birefringent tablets which he believed to be tridymite, but did not distinguish between the two materials. The one was probably cristobalite, and the other undoubtedly tridymite as he believed. Mansfield and Ross (1935, p. 321) also concluded that the devitrification products in welded tuffs from southeastern Idaho were tridymite and feldspar. Zirkel (1876, p. 165–168) reported tridymite in a rock from the Truckee Canyon region in western Nevada, and restudy of his thin sections by the authors has shown that this rock was a welded tuff. Zavaritsky (1947, p. 12) reported cristobalite and tridymite from a welded tuff from Russian Armenia. Thus tridymite was recognized, but the very fine grained intergrowths within the shards remained unidentifiable until the application of X-ray methods.

Tuffs from Katmai and Peru collected by Fenner, those from Idaho collected by Ross and Smith, and those from New Zealand collected by Ross were examined by means of X-ray, and in all these the characteristic devitrification product was cristobalite; and subsequent examination of many devitrified tuffs have shown cristobalite. The reason for concluding that devitrified tuffs were characterized by tridymite seems obvious. Tridymite developing in cavities occurs as crystals large enough to be readily identified, but the cristobalite cannot be so identified, although the microscope shows that the intergrowths contain a mineral of very low index of refraction. The presence of two distinct silica minerals seemed improbable, and it seemed a logical assumption that tridymite, the mineral that was directly observable, was representative of the other product of devitrification.

In general the cristobalite-feldspar intergrowths that have developed entirely within a shard are compact, and without observable pore space. This is confirmed by the specific gravity of materials such as those illustrated in figure 68, which is similar to that of crystalline flow rocks of like composition.

Devitrification tends to be more prevalent in tuffs that have undergone compaction and welding, but very porous ones may also be devitrified as in the tuff shown in figure 17. The development of crystals during devitrification and vapor-phase crystallization has commonly brought about a hardening or induration of the tuff without the intervention of welding. Fenner (1948a, p. 884) has discussed such tuffs from Arequipa region of Peru and called the resulting material "sillar."

The aggregate of cristobalite and feldspar that develops during devitrification may assume very different patterns and these merit some discussion. In figure 51, the tuff structure is greatly compressed, but is still fully recognizable, despite the development of devitrification products whose pattern transects that of the shards. In figures 59 and 77 compression and devitrification have marred, but not entirely obscured, the tuff structures, as shown under normal illumination. On the other hand, the same area under crossed nicols (fig. 60) shows only a coarse-grained crystal aggregate with the tuff structure entirely obscured.

The most characteristic and widespread type of devitrification product is that where the growth of the replacing feldspar and cristobalite began at the grain boundary, and the waves of crystal growth met at a central zone of discontinuity that forms a dark line, as illustrated in figures 71–74. This represents the axiolitic structure of Zirkel (1876, p. 166, 167) and is illustrated in the reproduction of a drawing by Zirkel (fig. 95). In this type of devitrification each of the structural units is a replica of a glassy shard unit. This type of devitrification has a minimum effect in modifying shard structure as is shown in figures 71–74. This axiolitic structure is widespread in devitrified tuffs and is even discernible in the Precambrian welded tuff from Morocco (fig. 98). Axiolitic structure has been observed only in ash-flow tuffs, and seems to provide excellent criteria for distinguishing between ash-flow and ash-fall tuffs. Possibly it could develop in fused tuffs (see p. 26) but has not been observed.

In some tuffs, devitrification began only after thorough welding and compaction, and the feldspar-cristobalite intergrowths show continuity across large areas of tuff structure. This may or may not have important effects in obscuring the original shard structure. In figures 69 and 70, this development of feldspar and cristobalite has not markedly obscured the tuff structures.

In figure 51, the tuff structure is less well defined, but this is due to extreme stretching during welding, rather than to the development of devitrification products. In figure 60, a very coarse grained parallel aggregate of feldspar and cristobalite is shown under crossed nicols. However, under normal illumination of the same area, the tuff structure, although greatly modified during welding, is still recognizable.

In pumice grains in which there has been complete collapse, with elimination of pore space, but perhaps some re-solution of volatiles, there is a strong tendency for the development of an uncommonly coarse grained aggregate of feldspar and cristobalite. In figures 57, 58, and 61 and 62, the structure in pumice grains has been almost completely destroyed, but has been retained in the enclosing shards.

The most severe destruction of tuff structures seems to be the result of the development of spherulites, with their radial aggregates of feldspar and cristobalite. In figures 55 and 56, radial groups have destroyed the structure over most of the area illustrated, but small lenslike areas retain tuff structures.

Complete destruction of tuff structure is illustrated in figures 63–65. In figure 63 a very large spherulite is illustrated on the right and a plumose structure has developed. In figure 64 the concentric structure characteristic of many spherulites is illustrated. These spherulitic structures developed in welded tuffs differ in no way from those occurring in many rhyolitic extrusive rocks. The identity of such rocks may be determined from geologic relations, or inclusions of materials of clastic origin may indicate ash-flow origin. On the other hand the origin of rhyolitic rocks with strongly marked spherulitic structure may be indeterminable. Not all spherulites cause destruction of pyroclastic structure, as shown in figures 54, 67–69, and 92. The studies of many hundreds of thin sections from different parts of the world indicate that most ash-flow tuffs are readily recognizable by means of thin-section studies. However, the foregoing discussion of devitrification structures indicates that a few may have lost all identifiable tuff characteristics.

Marshall (1935, p. 31–32) considered the possibility that devitrification could destroy all direct evidence of original ash structure and says,

> Obviously the question arises as to whether the rocks of some of the areas of spherulitic rhyolite, of relatively coarse texture, in which no remnant of ignimbrite origin is evident, have actually been formed in this way.

This suggestion is strengthened by

> The frequent occurrence of spherulitic rocks in beds which are almost horizontal, without a scoriaceous surface, without obsidian selvages, with a columnar structure, and with a relatively crumbly nature * * *.

Studies of ash-flow tuffs from other localities raises the same question posed by Marshall.

Lithophysae seem to be much less common in welded tuffs than in the corresponding extrusive rocks, but differ in no principal character. However, very abundant lithophysal cavities are especially conspicuous in one widely occurring welded tuff in southeastern Idaho (figs. 49 and 52). These cavities are the result of the release of volatiles during devitrification and suggest that this particular ash flow had retained an uncommonly large proportion of volatiles in solution in the glass. The so-called thunder egg shown in figure 67, represents an uncommonly large lithophysa which had developed in a welded tuff from Oregon. The inner cavity was subsequently filled with chalcedony.

PHYSICAL CHEMISTRY

The concept of the emplacement of pyroclastic materials by flowage, and in many occurrences their subsequent welding into a compact rock with many of the relations of lava flows, is so remarkable that the full recognition of this mode of origin was accepted but slowly. The seeming improbabilities of such a mechanism are so real that a very detailed consideration of the physical and chemical factors involved in ash flow, welding, and devitrification seems to be imperative.

A consideration of the mechanisms of the formation of welded tuffs and related materials includes only a part of the broader concept of igneous activity. Several factors involved in volcanism, such as the ultimate source of igneous materials and the mechanism of their migration from that source, will probably long remain controversial. A study of ash-flow tuffs is concerned with one phase of volcanism, that seems to be a late and superficial phase of igneous activity. However this late activity makes important relations available to direct observation, but others that occur in depths are not so observable.

A fuller understanding will be desirable of eruptive mechanisms in general, the volatiles that characterize them, the heat relations in an ash flow, and the flow mechanism of plastic ash shards suspended in an atmosphere of red-hot turbulent gas—the latter a unique flow medium. However, a synthesis of direct observation, geologic studies, thermodynamics, physical chemistry, and geophysical experiment seems to provide the basis for an attempt to understand the principal factors involved in the eruptions, vesiculation, explosive disruption, flowage, emplacement, welding and devitrification processes, and vapor-phase reactions that have produced welded tuffs.

Not all geologists are agreed about the relative importance of differentiation in the formation of the different magma types. However, concentration of volatiles accompanying progressive stages of differentiation and crystallization seems to be well established. The later products of differentiation, commonly contain a concentration of volatiles, and so provide the necessary mechanism for explosive, pyroclastic eruptions. As volatile-laden magmas rise to regions of diminished pressure these volatiles tend to escape, and commonly escape explosively. Variations in volatile content and pressures on the system at the time of eruptive breakthrough probably determine both the violence of the eruption and its nature, whether ash flow or ash fall.

The physicochemical factors controlling the eruption and later history of welded tuffs, nonwelded tuffs and related pyroclastic materials are: (a) The chemical composition of the magma from which they were formed; (b) the proportion and character of the volatiles originally dissolved in the magma; (c) the temperature at the time of eruption and at successively later stages, until all reactions cease; and (d) the physical and chemical reactions at successive stages in the genetic history of the tuffs. Such physical relations as thickness of the tuff deposit and the hydrostatic pressures developed in the system, total volume, slope on which they were deposited, and the tuff textures that affect retention of heat and volatiles are also essential factors in the formation of ash-flow deposits. The eruptions of the magma, its vesiculation, flowage as a turbulent mixture of ash and gas, welding after coming to rest, and final devitrification are all functions of the above relations.

The initial difference between ash-fall and ash-flow eruptions is probably only the relative gas-controlled violence of the eruptions. However, this is the basis for fundamentally different posteruption processes. The ash-fall material has been blasted high into the air where its magmatic volatiles were largely dissipated and where it was quickly chilled and its magmatic history brought to an end. In contrast the ash-flow tuffs have been emplaced by mechanisms that conserved heat and at least some of the volatile constituents. Thus a series of physical and chemical relationships was initiated which have left a partial geologic record. This section will explore the physical and chemical factors that seem deducible from that record. This means that the study of the origin of ash-flow tuffs is a geologic problem, buttressed by available direct observation, experiment, and chemistry and theories of mechanics and physics.

HEAT

A source of heat adequate for welding of ash-flow tuffs after eruption and travel for long distances has presented a major problem for geologists. Transportation through the air was long the only recognized mechanism for dispersal of ash from volcanic eruptions. However, this mechanism would involve such a loss of heat, that welding after wide dispersal seemed to be precluded, and this deterred geologists from accepting the welding of tuffs. The wide application of the term "nuées ardentes" and its equivalent "glowing clouds" to describe the dispersal mechanism has tended to perpetuate the concept of cloud-borne materials in contrast with the ash-flow mechanism of dispersal. A dispersal mechanism compatible with conservation of heat became understandable only when ash flowage, rather than cloud dispersal, came to be recognized. However, the entire problem of heat conservation during the formation and transportation and emplacement of ash-flow materials remains to be considered.

Many measurements of the temperature of magmas at the time of extrusion have been made. Some of these have been summarized by Daly (1933, p. 68) and indicates a range from about 1,050°C to nearly 1,200°C. Perret (1950, p. 55) has described temperatures of 1,000°C to 1,150°C at Vesuvius. A large proportion of the recorded temperature measurements were made at basaltic or andesitic centers, and much less is known about the temperature in rhyolitic centers. However, the experimental work of Goranson (1932, p. 234) showed that a dry granite would be completely molten at a temperature of 1,050°C. He (1932, p. 229) found that at 1,500 bars pressure and with 3.8 percent H_2O, the granite became completely molten in 3 hours at 900°C. Bowen and Tuttle (1953, p. 50) found that granite melts at about 720°C under 1,000 atmospheres pressure of water, and at about 640°C under 5,000 atmospheres. Ingerson (1955, p. 346) remarks "These figures are much more in accord with field and mineralogical observations on granitic intrusions than are anhydrous melting temperatures." Explosive rhyolitic magmas are erupted under a sudden release of pressure, and so the foregoing figures do not directly apply to their temperature or volatile content. A knowledge is desirable of the temperature and pressure at which quartz phenocrysts began to form, volatile content of the magma, and the pressure and depth at which vesiculation began. However, the temperature of a rhyolite magma was much lower than that of dry fusion of granite; a temperature of about 900°C, or perhaps even less seems probable. Clearly it was below 1,000°C.

Some geologists have postulated reactions subsequent to initial eruption that supplied exothermic heat, and of these, Fenner (1950, p. 600–601) believes that exothermic reactions developed during the exsolution of volatiles from the molten magma are a fundamental factor in welded-tuff formation. He says,

> We are now prepared to consider what happens when fugitive constituents are given an opportunity to escape * * *. In these events each individual reaction between the infinitesimal units is accompanied by a minute heat effect positive or negative, but the system as a whole is so immensely complicated, and there is so little information in the reactions of separate constituents, that no calculation of the net heat effect is possible. The evolution of heat might be very great * * *. Or, on the other hand, the net effect in the system as a whole might be negative.

Fenner further considered field evidence of exothermic reactions, but this was based on relations in Katmai crater, rather than those of the "sand flow" in the Valley of Ten Thousand Smokes. The tuff of the "sand flow" shows no indications of solution of phenocrysts or of included andesitic rock fragments and so there is no evidence of the superheat that Fenner believed was indicated at Katmai.

The study of ash-flow tuffs from many other locations has shown that magmas from which welded tuffs are derived reached the surface with different, but in general with important amounts of phenocrysts. Feldspar phenocrysts may be euhedral, or sharply angular, and fractured crystals rarely show the effect of rounding by re-solution. Quartz commonly shows embayment but in no greater degree than in extrusive lavas of the same composition; this embayment probably occurred before eruption. Augite grains and rock fragments derived from andesitic rocks rarely show significant reactions with an enclosing rhyolitic magma. Calcic feldspar grains derived from the rocks traversed by the magma on its way to the surface, seem in some occurrences to have been out of equilibrium with the magma, and show evidence of alteration or resolution.

The relations between included crystal grains and the magma are not primarily different from those observed in extrusive rocks. Thus, in general, tuffs show no evidence of superheat, or for any addition of a substantial amount of heat subsequent to eruption. The original heat of the magma seems to be all that is involved in the observable relations. A few welded tuffs are uncommonly low in phenocrysts and may have been uncommonly hot. The adequate heat for welding within an ash flow must be sought in connection with other physical and chemical relations that tended to conserve this initial heat supply.

VISCOSITY

The viscosity of glasses with a large proportion of SiO_2 and Al_2O_3 is so high that it has an important effect on the mechanism of explosive ash-flow eruptions, and especially on welding and distortion of shards. Viscosity data for silicate melts have been discussed by Bowen (1934). Experiments on an albite glass indicated a viscosity of about 10^8 poises at 1,150°C. The viscosity of a rhyolite glass, although somewhat higher, would be of a similar order. An andesite glass with 51.00 percent SiO_2 had a viscosity of about 3.1×10^4 poises at 1,200°C. Macdonald (1954, p. 172), by basing his calculations on the rate of flow, arrived at a viscosity of 2×10^4 poises for the 1950 Honoku flow at Mauna Loa, but thought that the figure was too great. These figures indicate the very high viscosity of rhyolitic magmas and the much lower viscosity of andesitic and basaltic ones. No quantitative data are available on the effect on viscosity of variations in temperature or the addition of H_2O. However, the experiments of Shepherd on the vesiculation of glass give some roughly qualitative information about the effect of volatiles on viscosity. Shepherd (1938, p. 340–341) states,

> For these 'wet' glasses (and the same would be true of the mother liquor of a crystallizing magma) a rapid change in the apparent viscosity is caused by relatively insignificant concentrations of volatiles. When a block of No. 5 [1.25 percent volatiles] reaches the vesiculating temperature it flows, i.e., froths, around and through small obstacles, or in a tube it froths all over the inside. But once volatiles are out, the septa and shreds of glass remain indefinitely rigid. It requires much time and a much higher temperature before the mass begins to gather itself together again. This quick shift from fluid to rigid has obvious importance both for volcanology and petrology.

Shepherd further states (1938, p. 343),

> The above-cited experiments on the relations of volatile content to viscosity have an important bearing on the mechanism of extrusion and lava flows. In the interval where vesiculation occurs the glass is notably fluid, the expanding pumice can froth around and between obstacles. But once fully expanded, that is to say, once the volatiles have been liberated, the foam becomes rigid.

VOLATILE COMPONENTS

Direct knowledge of the amount, volume, and the chemical character of the volatiles taking part in an explosive volcanic eruption is lacking, and only inadequate indirect observations are available. Collections have been made from secondary vents, but it is not known how well they represent original composition and they tell little about the original proportion of volatiles. Moreover, most such collections have been made from basaltic or andesitic lavas, and very much less is known about volatiles from rhyolitic ones.

Volatile constituents are essential in the entire sequence of events resulting in welded tuffs. They probably take part in the rise of the magma into the explosive eruptive vents, and they are most obviously important in the vesiculation and eruption of this magma. They are part of the gas-ash mixture that constitutes the ash flow and they are partly released from solution in the glass shards during flowage. Some volatiles have remained in solution until after the ash flow came to rest where they were a factor in lowering the temperature of welding, and promoted devitrification and the formation of vapor-phase minerals in open cavities. Some of the primary volatiles probably remained in solution in the glassy parts of ash flows.

The studies of volatiles in obsidian and associated perlite by Ross and Smith (1955) have indicated that most glassy volcanic flow rocks which have any degree of permeability have undergone postdepositional hydration. The same detailed comparisons have been possible with glassy ash-flow tuffs, but the high permeability of nonwelded ash-flow tuffs indicates that they too have undergone hydration. This is confirmed by the similar water content in the two types of materials, that is, of pumice and obsidianlike welded tuff. Only a few welded tuffs studied by the authors seem to have escaped hydration. One of these, a specimen from southeastern Idaho (figs. 9 and 10), contained 0.15 percent H_2O, while another part of the same flow contained 3.06 percent H_2O. These relations indicate that pristine water characterized the one specimen while the other had undergone hydration. The retention of even 0.15 percent H_2O is significant because this has been retained throughout all the volatile-controlled episodes that preceded cooling. Moreover, the physical effect of volatiles is greatly disproportional to their amount.

WELDING

Not all ash-flow materials have become welded, and others are welded only in some part of the flow. However, welding is one of the most significant features of ash-flow materials, and probably the one which has caused the most misunderstanding of ash-flow mechanisms. For this reason welding merits a detailed discussion.

The factors to be considered in welding are as follows: (a) The initial heat of the magma; (b) dispersal by flowage; (c) insulation in thick ash flows; (d) the effect of volatiles.

Ash flows must come to rest with substantial amounts of heat. The dispersal by flowage, and the speed of movement are necessary factors in the conservation of the heat which is required for welding after ash flows come to rest. No estimate, not even a vague one, of the speed of dispersal of the great ash flows of the past is possible, but the speed of some of the minor ones have been estimated as follows: Eleven to 26.6 meters per second, or 60 miles per hour at Pelée (Lacroix, 1904, p. 203); 33 meters per second, or 74 miles per hour at Pelée (Perret, 1937, p. 96); 100 miles per hour at Mount Lamington (Taylor, 1954, p. 86).

The great flows that spread for many miles probably moved even faster. Thus, movement is so fast that the time for cooling during flowage is short.

Rock materials are very poor conductors of heat, and would be still poorer with substantial amounts of pore space as in poorly consolidated materials. Thus, tuffs tend to remain hot long after they come to rest. In describing the eruptions at Pelée, Perret (1950, p. 95) says,

> Below the surface weeks after the passage of a nuée, a walking stick was burned at a depth of thirty centimeters or less * * *. So different was the more fully air borne ash which reached St. Pierre in the great nuée of May 8, 1902, that although its temperature on arrival is believed to be at least 800°C * * *. Negroes entered the ruined town in the afternoon only eight or nine hours later.

Kozu (1934, p. 143) has given the results of temperature measurements on ash-flow materials of the eruption at Komagatake, Japan, of 1929. At a depth of only 40 cm, and 8 to 11 days after the eruption, the temperature at 6 different places ranged from 510° to 310°C and about 1 year later the temperature ranged from 210°C down to 28°C at the same depths. A temperature of 510°C was probably too low to allow welding, but perhaps not excessively low; and had it been a thick flow, welding temperatures would probably have existed in some deeper part of the flow, and persisted for a long time.

The reduction of the viscosity of glass by the presence of small but significant amounts of volatiles discussed in the preceding section would be a factor in promoting the distortion and compaction which normally accompanies the welding of tuffs.

Many pumice fragments in welded tuffs show evidence of lower viscosity and greater distortion than the associated ash materials. Figure 47 illustrates a pumice area which was so plastic that it was distorted against an area of more rigid welded tuff. Figure 48 shows strong distortion of a pumice area. The complete elimination of porosity in many pumice fragments indicates the same relation, and that the vapor-phase material in the original pumice pores had been eliminated.

The pumice was originally inflated by the exsolution of its magmatic volatiles. The hot highly viscous glass walls of the pumice had a strength that a cold brittle glass would not have had. Therefore the vesicular pores of the viscous glass were probably capable of retaining at least part of the original volatiles. Experiments show that the volatiles involved in the expansion of a pumice are about 0.1 to 0.3 percent and some part of these would remain trapped. When this pumice collapsed probably some part of these trapped volatiles would go back into solution in the glass of the pumice. This suggests a possible explanation of the lowered viscosity of pumice fragments, as pointed out by Shepherd (1938, p. 343) when he says, "A mass of foam trapped and subjected to heat and water at sufficient heat and pressure will, of course, collapse and become fluid again." His study indicates that even 0.1 percent of H_2O would have an appreciable effect on viscosity of a glass. The relations in the pumice differed from those in the associated ash in which the volatiles escaped into intergranular spaces when not trapped as they were in the pumice vesicles.

Several geologists have studied the temperature of welding in ash-flow materials. Marshall (1935, p. 21) believed that because tridymite, with a minimum stability temperature of 870°C, was present in the New Zealand ignimbrites, this established that temperature as the minimum for their emplacement. He did not understand that both tridymite and cristobalite normally form as metastable minerals. Sosman (1927, p. 786) states,

> It might appear at first thought that the occurrence of one of the high temperature forms of silica in a rock is evidence that the rock was about 1470°C (cristobalite) or above

870°C (tridymite). But the tendency shown by silica to deposit in metastable form spoils this part of the argument. However, Marshall (1935, p. 22) noted that quartz was present and preceded tridymite in time of formation, and he was at a loss to explain this relation.

Gilbert (1938, p. 1856) based his conclusions on temperatures in the Bishop tuff on the temperature of the conversion of part of the green hornblende to basaltic hornblende. This caused him to state, "The only safe conclusion is that the temperature of emplacement could not have been very much higher than 750°C, for if it had been, all the hornblende should have been converted to basaltic hornblende."

Shepherd (1938, p. 342) reports experiments on the fusion of rhyolitic glass from Cerro No Agua and states, "But for anything one would call flow in the field sense, temperatures above 600°C are needed * * *."

Boyd and Kennedy (1951, p. 327) experimented on the welding of rhyolitic pumice from Mono Craters and state that "The pumice was found to weld at a temperature ranging from 775° to 900°C." Because the glass of ash-flow materials probably contained at least 0.15 to 0.3 percent of H_2O, the welding temperature would probably have been somewhat lower than this.

A report on the investigations of the Carnegie Institution of Washington Geophysical Laboratory for 1953–54 cites the studies of Boyd (1954, p. 139) at Yellowstone National Park. Boyd concludes,

> A thermodynamic analysis of the eruptive process [of avalanches of fragmented viscous lava] suggested by field evidence has been undertaken. The temperature interval between the original magma temperature and the welding temperature of the erupted tuff will have a maximum value of 100°C; in the average case it will be less.
>
> The amount of heat lost during emplacement of a tuff avalanche will depend primarily on the thickness of the tuff flow, the manner in which the flow moves, and the time elapsed during emplacement. Reasonable value for all these quantities can be found from either field evidence or from data available on nuées ardentes. Assuming a collapsed thickness of 30 meters, an average time of emplacement of one hour, and turbulent flow in the moving avalanche, the loss of heat during emplacement will reduce the temperature by less than 10°C—a value well within the estimated limits.

These figures are reasonable approximations for ideal ash-flow conditions, but many ash flows are probably not ideal. That is, the ash flows have been subject to mixing with air and their distal ends have come to rest at much lower temperature than the initial eruption temperature. These differences in temperature may be very real, as can be readily seen by the changes in amount and degree of welding that take place in many single ash-flow sheets between source and distal end.

Recent experimental work by Smith and Irving Friedman (written communication, 1956) has shown that welding of glassy rhyolitic ash and pumice can take place at temperatures at least as low as about 580°C. These experiments were carried out under a water-vapor pressure of about 300 psi (pounds per square inch) and a mechanical load of about 500 psi. They believe that pressure conditions of this order of magnitude could exist in ash flows having a precollapsed thickness of about 800 feet and a density of 1.5, or about 1,200 feet and a density of 1.0.

The physical relations within an ash flow may be restated as follows:

1. Rhyolitic tuffs are derived from a magma with an initial temperature not greater than 1,000°C, and probably below 900°C. Andesitic magmas probably reach a maximum of about 1,150°C.
2. The viscosity, especially of rhyolitic magmas, is high but not so high as to inhibit collapse and welding of shard materials under load.
3. Volatiles, at least in minor amounts, are recorded in most welded tuffs. These reduce viscosity and lower the temperatures of welding.

Relations that bear on heat conservation are as follows:

1. Pyroclastic materials commonly escape to the surface without superheat, and show no evidence of later acquiring substantial amounts of heat.
2. Gas phenomena accompanying ash-flow eruptions are powerful and the volumes of gas are large, but the mass is small compared with that of the ash.
3. Because the mass of gases that escaped during flowage is small their escape does not remove large amounts of heat from the system.
4. Ash flows move with great rapidity and the time effect on cooling is small.
5. The mechanism of dispersal is that of a gas-shard mixture of marked density and it rides close to the ground. The materials are not airborne as in ash falls.
6. Ash-flow materials are very poor conductors of heat.

These relations seem to indicate that the magmatic heat inherent in an ash flow is effectively conserved and adequate for welding.

The physical chemistry of the welding process is complex and the relative effects of the variables are difficult to evaluate. However, the relations in welded tuffs are similar to those known as sintering by the glass technologist, and some of the research on glass sintering helps the understanding of welding in volcanic ash.

The relations in sintering have been outlined by Eitel (1954, p. 1047) and are summarized as follows:

A minimum temperature must be attained for the initiation of the sintering reactions and atomic bridging. The mobility of the atoms or atomic groups must have attained a minimum intensity that is sufficient for a beginning of place exchange. The inference seems to be that the atoms and molecules must vibrate so intensely around their structural equilibrium positions that a large number of them are able to exchange places with surrounding atoms or molecules.

Eitel (1956) published a "free translation" of a series of papers by Carl Kröger (1952–55), and in a supplemental discussion further amplified the mechanisms of sintering, which are abstracted as follows:

The reactions in the solid system composed of individual units depend on the following factors:

1. A necessary threshold mobility of the atomic and molecular particles in the solids, along their boundary zones.
2. The temperature of a molecular exchange of place, under the action of thermal energy, is a function of fusion points. In a glass system this implies an adequate reduction of viscosity, which is dependent on temperatures and volatile content.
3. Sintering (welding) involves a real "creeping or flow factor." That is, if two units have an intimate contact, particles from both solid parts will diffuse along the boundary surfaces.

The rate of displacement will depend on the inner mobility (yield value viscosity) of the material, the surface tension of the material surrounding the medium, and the hydrostatic pressure under which the material is standing.

Mobility of the particle material at the elevated temperature may mean a partial flow in a liquid phase.

The above factors that control sintering apply primarily to crystalline materials, whereas in the welding of tuffs the materials are noncrystalline (glassy). The materials are also plastic, although the viscosity is so high that they will fracture under sudden stress. That is, glassy materials have properties of solids such as to make these factors of sintering applicable to an interpretation of the welding of tuffs. The glassy character would seem to simplify rather than complicate this relation.

The factors that control welding are: (a) The presence of volatiles; (b) pressure within the system; (c) intimate contact of the individual particles; (d) threshold mobility within the system (adequate temperature); (e) inner mobility (yield value viscosity and surface tension); and (f) creeping or flow factor.

These factors are interrelated and not entirely independent. The foregoing outline may now be specifically applied to the consolidation and welding of tuffs.

The tuffs come to rest in a heated condition, with welding initiated at about 650° to 700°C, and perhaps reaching about 900°C in the hotter tuffs. This provides them with a plastic yield, although the viscosity is high in glasses of rhyolitic composition. They contain small amounts of dissolved volatiles that have an important effect in reducing viscosity. After coming to rest the tuffs are under a static load, depending on the thickness of the overlying material. Porous glassy tuffs are exceedingly poor conductors of heat and remain hot probably for years.

Shards and other glassy fragments, as formed by explosive eruption, are sharply angular and would come to rest touching one another only at points, and with a large proportion of interspaces. Under load, and with adequate initial mobility, there would be plastic yield accompanied by varying degrees of distortion and accommodation of grain to grain. This plastic yield would, with time, increase the areas of contact between individual particles, and under optimum conditions there may be nearly complete elimination of pore space. In the presence of volatiles some of the particles would be adsorbed on the grain surfaces even at temperatures of 700°C. The effect of all these factors would tend to promote a bridging effect and a transfer of materials across surfaces of intimate contact.

In the system here postulated volatile components were present, both as a vapor phase and in solution in the glass. The vapor phase may have been a factor in some transfer of materials, but it did not initiate any new phase (crystalline). A crystalline phase did not develop until after welding.

Where viscosity is low and where there is contact only at points, welding may be confined to these small areas and recognition of welding under the microscope will be difficult. On the other hand, a combination of adequate pressure and other factors promoting initial mobility may combine to permit thorough accommodation of grain to grain, and result in the welding of tuffs into a compact obsidianlike glass.

The glass film that forms on the contact between two glass shards might be thought of as a secondary glass derived from the original glass. The intershard films are too thin to study in any detail, but differ slightly from the original or primary glass. In the glassy pumice from Argentina (figs. 83 and 84) the intershard film is colorless, while the original shards are brown. The lighter color is due in part to the nontransfer of pigmenting dust material, and indicates a slight difference in the composition of the two glasses. This does not seem, however, to constitute any discontinuity of phases.

The relations shown in figures 59 and 60, and in figures 67–70, are especially significant. Here there was almost complete elimination of pore space so that shards had been brought into complete contact with one another previous to devitrification. The continuity of the glass structure had become so complete that crystal growth of feldspar and cristobalite took place directly across the zone of union between original shard boundaries. The originally fragmental glass has become a structurally homogeneous medium, that presented no impediment to crystal growth across the former zone of discontinuity. This would seem to represent welding into a single glass phase previous to the growth of crystals across the former zone of contact.

The obsidianlike tuff illustrated in figures 9 and 10 has remained glassy, but the establishment of complete physical continuity seems evident. The collapsed pumice fragments have lost all trace of the original pumice structure (fig. 45) and here a complete continuity of structure has been established.

DEVITRIFICATION

Not all ash-flow tuffs have undergone devitrification; many are devitrified only in part, and have remained glassy at the top and base. Nevertheless, devitrification is one of the most distinctive characteristics of ash-flow tuffs, hence the physical and chemical factors involved in devitrification are of especial interest. The factors controlling devitrification are: (a) Chemical composition of the tuff; (b) chemical composition of the accessory volatiles; (c) rate of cooling; (d) temperature of devitrification; (e) identity of the minerals formed; and (f) stability relations of these minerals.

The chemical composition of the tuff may be closely determined, although it may have been very slightly modified during devitrification in the presence of volatiles.

The amount and chemical composition of the volatiles retained in a glass would probably not be greatly different from that discussed in connection with welding. This similarity indicates that the volatiles were present in the glass to the extent of not more than a few tenths percent. However, even this proportion would reduce viscosity and promote crystallization. The presence of volatiles during devitrification is indicated in figures 49, 52, and 67. In these specimens devitrification was related to the formation of vesicular gas cavities.

Rhyolitic tuffs seem to be more commonly devitrified than andesitic tuffs. The reason for this is not clear because high-silica extrusive flows show a much greater tendency to remain glassy than do andesitic ones. The difference may be due to a more effective retention of volatiles in high-silica glass shards than in andesitic shards.

The temperature of devitrification has a wide range, probably beginning immediately after welding and continuing to some problematical minimum temperature. However, once crystallization starts, it probably proceeds rapidly.

X-ray examination of ash-flow tuffs has shown that the devitrification products of dense shards are a fine-grained intergrowth of cristobalite and sanidine feldspar. On the other hand, tridymite, and more rarely cristobalite, have formed in vesicles and uncollapsed pumice fragments. The factors that determine whether cristobalite or tridymite develop are of interest. Where compact homogeneous glass is devitrified there is a diffusion of ions within the glass over very small distances, but there seems to be no vapor-phase transfer, although volatiles are in solution in the glass and help to promote devitrification. The same minerals form in collapsed pumice where free vapors do not collect. On the other hand, where the pumice does not collapse or where vesicles form, tridymite and feldspar form in the presence of vapors. There is vapor-phase transfer of materials at least for short distances. The formation of tridymite in a gas cavity is illustrated in figure 66. In rhyolitic welded tuffs tridymite and feldspar are the typical vapor-phase minerals, but more rarely biotite, amphiboles, and zeolites may form.

The metastable character of cristobalite and tridymite means that these minerals tend to invert to quartz, the stable allomorph of SiO_2. The geologic conditions that allow tridymite or cristobalite to persist, or that may promote inversion to the stable form are not accurately known.

Cristobalite and tridymite seem to have resisted inversion to quartz in all the very abundant ash-flow tuffs of younger Tertiary and Quaternary age that have been available for study, the only exception being those which have undergone alteration. Tuffs of Mesozoic age are less well known, and cristobalite has not been definitely recognized in tuffs of Paleozoic or older age. Upper Carboniferous tuffs from Corsica described by Bodenhausen (1955, illus. 21, 22) show evidence of fine-grained quartz. A specimen of welded tuff of Precambrian age from Sweden described by Hjelmqvist (1956) is characterized by quartz (examination by the authors). Welded tuffs of Precambrian age from the Anti-Atlas region of Africa have been described by Bouladon and Jouravsky (1954, p. 37–48), and samples have been made available for study. The shards illustrated in figure 98 still retain typical axiolitic structures, but these now contain only quartz and feldspar.

PHYSICAL PROPERTIES

INDICES OF REFRACTION

George (1924) has provided useful data for determining the approximate silica content of a volcanic glass by means of indices of refraction. The study of the effects of water in glasses by Ross and Smith (1955, p. 1080–1085) included their optical properties, and the effect of water in raising the indices of refraction. This showed that the presence of 1 percent of water would lower the indicated SiO_2 content (compared to a water-free glass) by about 2 percent.

Ash-flow tuffs commonly contain foreign material and these may give an incorrect indication of the character of the primary eruptive magma. Bonorino (1944) has described "ignimbrites" from near Malargue Mendoza, Argentina, and says, "The crystals are acid to basic plagioclase, and clinopyroxene, the two latter often associated as to suggest their common origin from a basaltic rock." A restudy of this material submitted by Bonorino (figs. 83 and 84) has indicated that the calcic plagioclase and clinopyroxene did have a common origin, but that these materials seem to have been derived from an invaded rock, probably an andesitic one. The index of refraction of the glass fraction (1.508 to 1.512) indicates that the eruptive material of the glass shards was much more silicic than the composition of the rock as a whole. For this reason the silica content of the glassy groundmass part of this rock was determined by the U.S. Geological Survey. The SiO_2 content of 67.20 percent indicated that the rock, without inclusions, was probably dacitic.

An important variable affecting the index of refraction of a glass is the state of oxidation of the iron. The total iron content of volcanic glasses may be as much as 7 percent or more, and in unaltered glasses is present in both the ferrous and ferric state. Such iron in solution in a glass gives it varying intensities of dull-brown tints, except in very low iron rhyolites, in which the glass may be nearly colorless.

The collapsed pumice fragments shown in figure 1 appear black in the hand specimen. Under the microscope this glass is nearly colorless while the groundmass glass (red in the hand specimen) is slightly brown. The colorless glass contains magnetite microlites abundant enough to permit a perfect separation from the nonmagnetic groundmass. The presence of magnetite microlites in the colorless glass is also observable under the microscope. In this glass the iron that was originally in solution was reduced to magnetite and segregated into distinct granules by reactions that took place during the collapse and welding of the pumice fragments. The elimination of part of the iron from solution in the glass and its collection as discrete microlites of magnetite has lowered the index of refraction of the colorless glass below that of the brown glass.

The different states of oxidation of iron, and the resulting changes in a glass are shown in the frontispiece where reproduction in color depicts relations that black and white illustrations could not reveal. The iron in the glassy tuff illustrated in the top photograph was oxidized and colloidally dispersed, as suggested by Iddings (1899, p. 407), probably during emplacement in the presence of oxygen from the air. A later change in the environment resulted in the partial reduction of the ferric iron, and its segregation as finely disseminated dustlike magnetite. Thus iron was removed from colloidal dispersion in the glass, leaving it nearly colorless, with an index of refraction abnormally low for a glass of this composition.

The dull-brown glass in the central part of the two large shards shown in the bottom photomicrograph seems to retain the normal ferrous-ferric iron relations of a glass of that composition; the index of refraction is intermediate, and characteristic of a glass of that composition. On the other hand, oxidation of most of the iron to Fe_2O_3, and its colloidal dispersion in the glass, has raised the index of refraction above that of the normal brown glass.

As may be seen from the foregoing discussion, several factors may have a marked effect on the indices of refraction of a glass, and caution should be exercised in determining the composition of a glass from its index of refraction. The glass fraction may differ in composition from the overall composition of the rock because of the presence of phenocrysts and the inclusion of alien minerals and rock fragments. The glass of tuffs has usually undergone hydration, which increases the index of refraction. If the glass has any appreciable proportion of iron the different states of oxidation will have a marked effect on the indices of refraction.

The phenocrysts of a volcanic rock may give an incorrect indication of the chemical composition as pointed out by Rittman (1952, p. 76) who states,

> The phenocrysts by themselves give very often a wrong idea of the real composition of the whole rock, because quite different kinds of minerals than those forming the phenocrysts may be present in the optically indeterminable microcrystalline groundmass, or may be potentially present in the glass. For example, many dacites, or even rhyodacites have been called andesites because their contents in quartz and sanidine occult in the groundmass were not taken in account.

Rittman shows the necessity of extreme reservation in assigning an andesitic character to a tuff on the basis of observable minerals. The rock in bulk may be much more silicic than suggested. Andesitic rock and mineral grains are so ubiquitous in welded tuffs throughout the world that their complete absence is rare. Where they occur in rhyolitic welded tuffs, their alien character is obvious; but in ash-flow tuffs of intermediate composition they may lead to incorrect identifications.

SPECIFIC GRAVITY

Most welded tuffs retain at least some pore space, and only a few specimens permit a determination of the true specific gravity. However, the specific gravity of four virtually pore-free rhyolitic welded tuffs is given as follows:

Specific gravity of dense rhyolitic tuffs

Character of material	*Locality*	*Specific gravity*
Glassy welded tuff	Valles Mountains, N.Mex	2.38
Obsidianlike welded tuff	Southeastern Idaho	2.34
The same tuff hydrated	Southeastern Idaho	2.40
Dense devitrified tuff	Oregon	2.47

The small difference in the specific gravity of glass (2.34, 2.38) and of dense devitrified tuff (2.47) might seem surprising, but this is due to the large proportion of cristobalite (specific gravity 2.32) in the tuff.

POROSITY

Ash-flow tuffs range from nonwelded, unconsolidated materials, to thoroughly welded tuffs with a density equal to that of the corresponding normal glass or crystalline rock. This range in porosity is illustrated in columnar sections of tuff deposits from three localities.

Marshall (1935, p. 29) gives porosities in a typical occurrence of the New Zealand ignimbrites. Fourteen nearly equally spaced samples were collected from a 250-foot cliff at Te Toki Point, Lake Taupo, New Zealand.

Porosity of acid rocks, Taupo-Rotorua, New Zealand, volcanic district

Sample	*Porosity (percent)*	*Sample*	*Porosity (percent)*
1	28.6	8	18.4
2	25.2	9	9.2
3	23.4	10	10.7
4	22.0	11	9.9
5	20.0	12	8.4
6	19.8	13	8.0
7	23.1	14	3.4

Marshall notes that samples 5 and 9 contained surface-deposited secondary silica.

Gilbert (1938, p. 1843) gives the following table of densities of a characteristic section of the Bishop welded tuff of California:

Porosity of Bishop tuff

Vertical distance from top of tuff (feet)	*Porosity (percent)*	*Specific gravity*
0	37	1.35
175 ± 25	17	1.9
250 ± 25	7.9	2.2
300 ± 25	4.6	2.26
400 ± 25	3.6	2.35

The welded tuff at Battleship Rock, Valles Mountains, N.Mex., was studied by the authors, and is shown in figures 42 and 43.

Porosity of Battleship Rock, N.Mex., ash-flow tuff

Sample	Distance below the top (feet)	Porosity (percent)	Sample	Distance below the top (feet)	Porosity (percent)
1	0	69	8	175	24
2	30	58	9	185	33
3	50	51	10	200	48
4	75	33	11	205	51
5	105	29	12	215	59
6	130	25.5	13	255	70
7	145	24			

Only a single unit is represented at the Battleship Rock locality and exposures present an excellent opportunity for detailed study. The porosity of the Battleship Rock ash-flow unit ranges from about 70 percent near the top, to 24 percent, about one-third the distance above the base, and then back to 70 percent at the base. In another locality, a part of the same ash-flow unit had undergone complete welding and elimination of pore space. Its specific gravity was 2.36 and this value was used in calculating the porosity of the section studied in detail. The variations in porosity are shown in the curve in figure 15.

Tuff units with maximum welding at or near the base, like those described by Marshall and by Gilbert, have been reported by others engaged in the study of ash-flow materials. The position of maximum load is commonly believed to be the reason for this position of maximum welding. On the other hand, the position of the greatest conservation of heat is also a factor in effecting maximum welding. For this reason many ash flows show relations similar to those in the Battleship Rock ash-flow tuff. Here maximum welding occurs about one-third of the distance to the top of the unit or about 80 feet above the base (fig. 3).

Most of the ash-flow tuffs of the Valles Mountains show similar relations. This same relation has been observed in the Rattlesnake formation of Oregon (T. P. Thayer, oral communication, 1950), and has been reported in Salvador by Weyl (1954b) and in some of the Aso flows of Japan (Williams, 1941b, p. 279–280).

ASH-FLOW MATERIALS OF INTERMEDIATE COMPOSITION

The preceding discussion has applied to ash-flow materials in general. However, in the Western United States these are dominantly rhyolites, dacites, quartz latites, or rhyodacites in composition, and for this reason a large proportion of the tuffs discussed have been rhyolitic in composition. The physical characteristics of rhyolitic and andesitic ash-flow materials are mostly the same, but the andesitic ones differ in some details and merit a

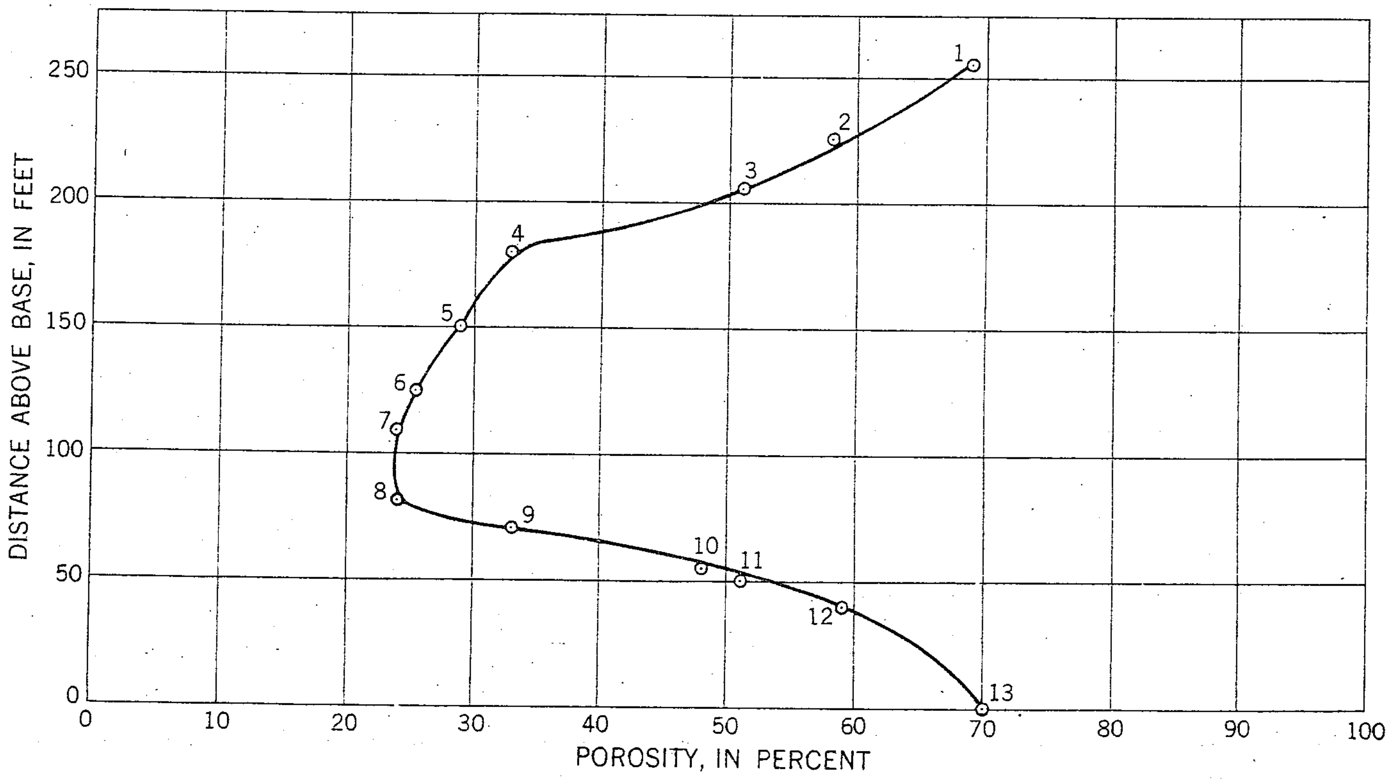

FIGURE 15.—Porosity of Battleship Rock ash-flow tuff, Valles Mountains, N. Mex.

brief discussion. The basaltic types of ash-flow materials seem to be comparatively rare, therefore they are considered together with those of intermediate composition. Ash flows of intermediate type have been described under a variety of names, including andesite, quartz andesite, latite, some so-called dacite, and in some regions, trachyte.

Ash flows of intermediate composition are dominant types in several regions, and have been described from Japan, Costa Rica, El Salvador, Argentina, Russian Armenia, and they occur locally in the Western United States. Specimens from the above localities, except El Salvador, are illustrated in figures 79–86.

Basaltic "scoria" flow materials have been described by Williams (1942) from Crater Lake, Ore., where they overlie dacitic "pumice flows." These are related to the eruptions that formed the caldera of Crater Lake.

Ash-flow tuffs of intermediate composition seem to be dominantly glassy, and in those available for study devitrification has been rare. The tuffs from Costa Rica, Argentina, Russian Armenia, and most of those from Japan, are glassy. The "schmelztuffe" from El Salvador described by Weyl (1954b) are glassy. An examination of figures 79–86 seems to indicate that the glass shards of intermediate composition tend to be platelike. In several of the figures the shards are almost shredlike. Few of them show forms derived from the shattering of rounded bubbles.

The disparity between the mineral grains recognizable under the microscope and the composition of the groundmass material has been described for the so-called andesite welded tuffs from Argentina (p. 45). The same disparity is strongly suggested by microscopic studies of other welded tuffs of intermediate type.

ANDESITIC ASH FLOWS OF COSTA RICA

A description presented by Williams (1952, p. 173–176) is the most detailed available of a typically andesitic welded tuff. His petrographic description of this rock is a valuable contribution to an understanding of andesitic welded tuffs, so will be quoted in some detail. One of the specimens (figs. 85 and 86, this report) described by Williams was collected by Gabriel Dengo, transmitted to the authors, and later divided with Williams to supplement his own collections. In his description Williams says,

> One of Señor Dengo's specimens is a magnificent example of a thoroughly welded tuff. The unaided eye sees abundant frayed disks of black glass, up to an inch in length and one-quarter as thick, set in an almost fluidal base of pale-gray glass shards, generally smaller, but equally drawn out and sinuous. Peppered throughout, and serving as nuclei around which the glassy lenses curve, are varicolored chips of andesite, up to half an inch in diameter, and smaller but more numerous phenocrysts, mainly of feldspar. A Rosiwal analysis shows that crystals total about 15 percent of the tuff. Among them, basic andesine-acid labradorite (12 percent) occurs in phenocrysts up to 2 mm long; smaller prisms of pale green diopsidic augite ($2V = 55°$) comprise 2 percent of the whole, and hypersthene forms less than 1 percent. Hornblende, biotite, and olivine are lacking. Lithic fragments of varitextured pyroxene andesite amount to 5 percent. The remainder of the tuff is made up of sinuous, tightly adpressed shards of clear glass varying in color from pale lilac and buff to deep brown, the darker ones corresponding to the black lenses seen by the unaided eye. None of the glass is devitrified, but some of the minute pores between the shards carry spheroids of cristobalite. Especially noteworthy is the wide range in the refractive indices of the glassy particles. In the palest wisps the index is as 1.510 ± .002; in the darkest, it increases to approximately 1.550. Most of the glass varies in index from 1.530 to 1.540. Even more remarkable is the fact that although most of the individual shards are composed of uniformly colored glass, some reveal a fine banding of pale and dark glass of notably different indices.

Williams (1952, p. 175) also states that another tuff in the area consists of 10 percent andesite fragments. In discussing the different types of glass in the tuff Williams says (1952, p. 176),

> * * * in the Costa Rica tuffs the individual shards are usually of one color or another. This confused mingling of minute varicolored shards of widely differing refractive indices, presents a difficult problem for which a satisfactory answer has yet to be found. It cannot be attributed to successive eruptions of different magmas; on the contrary, magma of heterogeneous character seems to have effervesced simultaneously from the feeding vents. There is no sign here of solution or even dismemberment of the included lithic fragments * * *. If the heterogeneity of the Costa Rica tuffs resulted from contamination, the process must have taken place at depth and proceeded so far as to leave no indubitable evidence.

DISTRIBUTION IN TIME

Some of the notably large ash-flow deposits of the world, and others that have been most important in the development of an understanding of them, have been mentioned (p. 14, 23). A compilation of known localities would provide useful references for several lines of geologic study, but is not within the scope of this paper. Moreover, papers reporting newly discovered occurrences of welded tuffs, or the extension of previously recognized areas, are appearing in ever-increasing numbers, and any list of known localities would soon be out of date. On the other hand, some consideration of distribution of welded tuffs in time seems to have significance, and for this reason a discussion of known pre-Tertiary occurrences of welded tuffs will be helpful.

Volcanic activity has persisted throughout geologic time, and probably welded tuffs have always been involved in that activity. A compilation of all recognized occurrences would show a very great preponderance of those in Tertiary and Pleistocene time with a remarkable decrease in their number in older rocks. No doubt their recognition will be precluded in many of these older rocks, but there is increasing evidence that detailed studies, backed by a knowledge of significant characteristics, will reveal a welded-tuff origin in many rocks that might otherwise be misinterpreted. The increasing interest in the geologic occurrence of welded tuffs has led to the recognition of several Precambrian occurrences within the past few years.

One of the major objectives of this report has been to present the characteristics of welded tuffs, as seen in those rocks in which there has been little or no postdepositional modification, and to trace significant characteristics into tuffs whose origin has been obscured by different changes. The authors feel that an intimate knowledge of significant features will lead to identification of increasing numbers of welded-tuff occurrences in older rocks.

MESOZOIC

The Brisbane tuff of Australia of Triassic age has been described by Richards and Bryan (1934, p. 51). A suite of specimens of the Brisbane tuff was received through the courtesy of Bryan and one of these is shown in figure 75. A great thickness of welded tuffs of Triassic age occurs in Inyo County, Calif., and has been studied by Ward Smith, U.S. Geological Survey (written communication, 1950). A Cretaceous age is assigned to glassy welded tuffs from Montana, which were studied by Barksdale (1951). Welded tuffs studied by Solovev (1950, p. 211) from the southern Sikhote-alin region of Siberia are said to be Late Cretaceous and early Tertiary in age.

PALEOZOIC

Tuff deposits of "Pelean" origin have been described from the Ordovician of Snowdon in Wales by Dakyns and Greenly (1905), and by Williams (1927). Oliver (1954) has described and given excellent illustrations of "welded tuffs" in the Lake district of England and in Wales.

Bodenhausen (1955) has given detailed descriptions of welded tuffs from the lower Carboniferous of Corsica. His illustrations present many of the relations that characterize devitrified welded tuffs. Some of these show a large proportion of lenslike areas with coarse-grained devitrification products, clearly representing areas that were originally pumice.

Ross (1958) has studied volcanic materials that occur in drill cores from a deep well (4,000 feet) in Clinch County, southeastern Georgia. One horizon in the well is characterized by welded-tuff fragments representing materials derived from some densely welded and devitrified tuff body. Above that is about 35 feet of material which was originally a glassy welded tuff that has been replaced by laumontite. Applin (1951, p. 9) concludes that these tuffs are probably of early Paleozoic age. Volcanic materials are widespread in southeastern Georgia and Florida, and welded tuffs will probably be recognizable in other localities of the region.

Weyl (1954b, p. 28, 29) has considered the possibility of welded tuffs in central Europe and says,

> The wide distribution and large quantity of younger welded tuffs pose the question of whether such rocks are not in existence also in the volcanic series of central Europe, but have escaped identification so far. Judging by the magmatic-tectonic occurrence of the younger welded tuffs and their chemistry, similar formations would be expected first of all in the region of an acid subsequent volcanism. Thus, they could be perhaps encountered in the system of sandstones, shales, and conglomerates of the lower Permian (Rotliegendes) in the central mountains of Germany. [von Gaertner called attention to tuffs of this system in the Forest of Thuringia] * * *.
>
> The porphyritic tuffs of the 'Rotliegendes' system include rocks, the description of which—mostly written in older times—fit completely the character of welded tuffs.

Weyl also calls attention to the streaked texture, coarse bedding, platelike jointing, and poorly delineated stratification in the tuffs of the Sturmheide porphyry and Kickelhahn porphyry. He has also mentioned the porphyry tuffs of the Black Forest and Oden Forest that suggest derivation from flows. Nuées ardentes were mentioned in connection with the origin of Trass in Brohltal.

PRECAMBRIAN

Rocks of Precambrian age that retain evidence of welded-tuff origin are of special significance. For this reason Bouladon and Jouravsky (1954, 1955) have made an outstanding contribution in presenting the first clear-cut evidence of ignimbrites of Precambrian age from the Anti-Atlas region of Morocco. The descriptions and illustrations presented by these geologists show good welded-tuff structures. Through the courtesy of Bouladon the authors received an excellent suite of these rocks.

The feldspar phenocrysts have been altered, but the shard structures show uncommonly good preservation. Traces of the parallel growth of devitrification structure in the individual shards (axiolitic structure) are still observable. A photomicrograph of one of these specimens is illustrated in figure 98.

Ignimbrites of Precambrian age have been described from the Dalarna region of central Sweden by Hjelmqvist (1956). His illustrations present excellent examples of welded-tuff structures. Several of these show marked distortion, but without loss of clear evidence of their true origin. The distorted welded tuff illustrated in figure 78 is derived from this same group of welded tuffs of Precambrian age (Hjelmqvist, written communication, 1956). The recognition of the character of this specimen caused Ross to communicate with Prof. P. Geiger concerning the occurrence of welded tuffs in Sweden. (See footnote by Hjelmqvist, 1956, p. 9).

Ross has identified welded tuffs from two deep wells in Texas, one, No. 4–B Masterson well, from near the Canadian River, Potter County, at a depth of 1,952 feet; and the other from the Phillips No. 1–A Stevens well, Bailey County, Tex., at a depth of 8,226 feet. A valuable paper on the basement rocks of Texas and southeast New Mexico has been published by P. T. Flawn (1956). This intimate knowledge of the basement rocks of Texas enabled Flawn to give the authors information about the geologic position of the aforementioned welded tuffs. He wrote (written communication, 1956):

> I believe that the rhyolitic rocks penetrated in both these wells are late Precambrian age and part of an extensive late Precambrian volcanic terrane which I have called the Panhandle volcanic terrane. I suspect that in a rhyolitic volcanic terrane as extensive as this one you would expect to find welded tuffs * * *.

Thompson and Williams (1956) have described glowing avalanche deposits of early Precambrian age in the Sudbury basin of Canada.

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FIGURES 16–98

FIGURE 16.—Glassy ash-flow tuff from South Sumatra collected by Westerveld. Characterized by platelike, slightly distorted shards. Note the absence of fracturing of the slender branches of the large shard near the right. An unusually massive shard lies in the upper third of the figure.

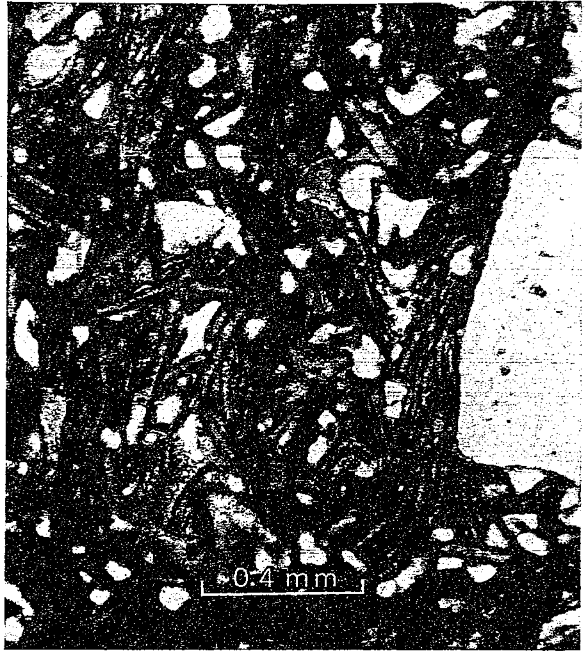

FIGURE 17.—Ash-flow tuff from the Ammon quadrangle, southeastern Idaho, collected by Mansfield. Composed of large platelike shards, which are completely nonwelded and with a large proportion of pore space (small white areas). Very coarse grained devitrification products (feldspar and cristobalite) have developed. A large feldspar phenocryst is on the right margin.

FIGURE 18.—Glassy ash-flow tuff from the Ammon quadrangle, southeastern Idaho, collected by Mansfield. The tuff is virtually nonwelded, but there has been slight warping of the shards. There is an uncommon number of unbroken nearly circular glass-bubble walls. There is a wide range in the size of the shards and interstitial dust is present. Phenocrysts are completely absent.

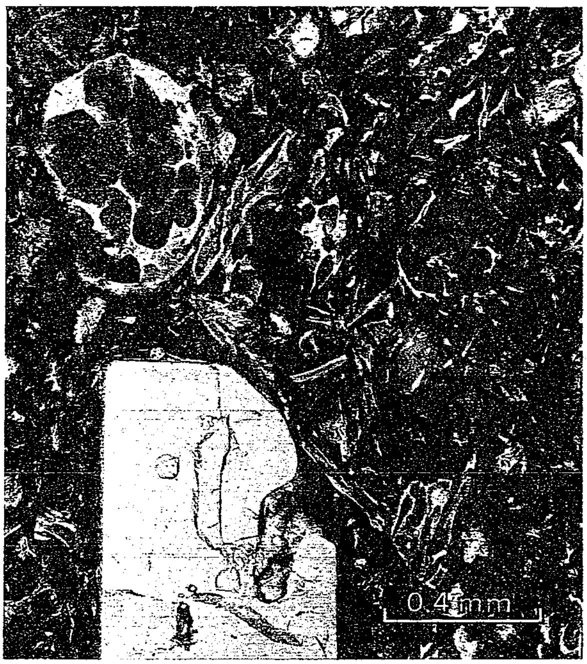

FIGURE 19.—An ash-flow tuff from Iceland, received from Tomas Tryggvason. There may be slight welding, but there is no distortion of the structures. A large euhedral plagioclase crystal at the bottom of the figure has been embayed on its right margin. The rounded area near the upper left corner is a pumice fragment with nearly round vesicles. Secondary alteration has resulted in the formation of a little bright-green celadonite.

PHOTOMICROGRAPHS OF NONWELDED OR SLIGHTLY WELDED TUFFS

FIGURE 20.—Ash-flow tuff showing alignment of shards due to orientation during emplacement by flowage rather than to compression. Several Y-shaped shards are observable. At the extreme right is a large twinned plagioclase crystal, embayed along its left margin.

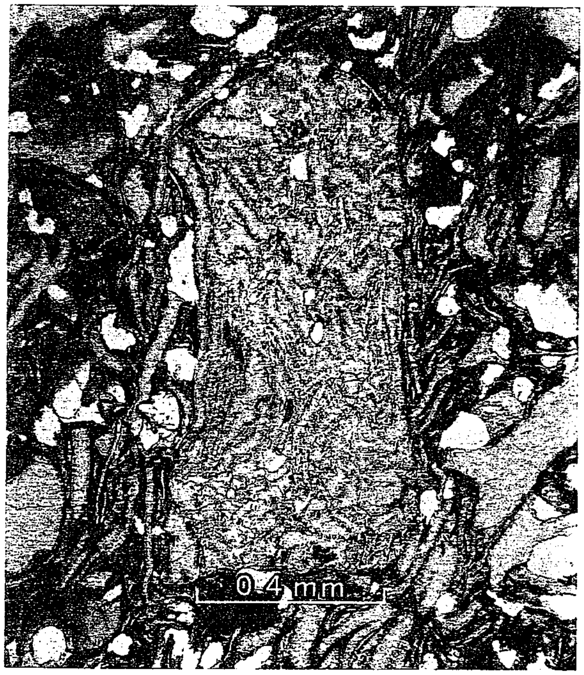

FIGURE 21.—The large central area represents a fragment of an older welded tuff enclosed in a younger tuff material. In the older tuff there is thorough welding and marked distortion of the shards. The younger tuff is poorly welded, but its shards show evidence of alinement. The small white areas represent pore spaces.

FIGURE 22.—Glassy welded tuff from South Sumatra collected by Westerveld (1942). This tuff is characterized by sharply angular shard fragments, many of which represent glass walls at the junction of several bubbles. The tuff is almost without phenocrysts.

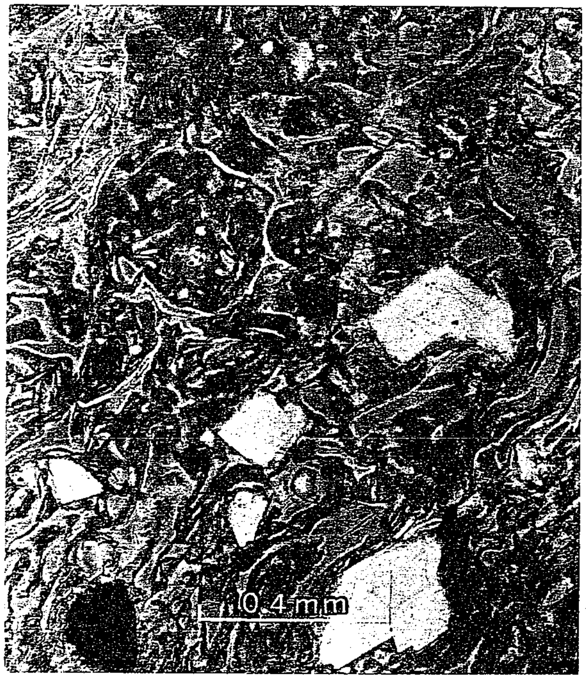

FIGURE 23.—Glassy ash-flow tuff from Barley Canyon, Valles Mountains, N.Mex., collected by Ross and Smith. The tuff shows only slight welding, but platelike shards on the extreme right are bent against the fragment of quartz. A large irregular bubble wall on the left encloses a groundmass of tuff fragments.

PHOTOMICROGRAPHS OF SLIGHTLY WELDED ASH-FLOW TUFFS

FIGURE 24.—Glassy tuff with a wide range in the size of the shards and with much interstitial dust. Near the upper left is a biotite crystal, but the Arequipa tuffs are, for the most part, very low in phenocrysts.

FIGURE 25.—Glassy welded tuff. Disruption during flowage or by explosive violence has resulted in a large proportion of fragments that lack characteristic shard forms, but a shard representing the glass walls between three bubbles lies in the upper part of the figure. The dark area is one of many fragments of andesitic rock. Very calcic plagioclase, also derived from alien invaded rocks, is present.

FIGURE 26.—Collected at Kampong, Getang W. of Hoetambolon Samosier Peninsula, Lake Toba. A glassy welded tuff with compressed shards molded against the phenocrysts. Most of the feldspar and quartz occurs as fractural angular grains, but some show rounding by resorption. This specimen illustrates an uncommonly crystal-rich welded tuff. Biotite (dark plates) is characteristic of the Sumatra tuffs.

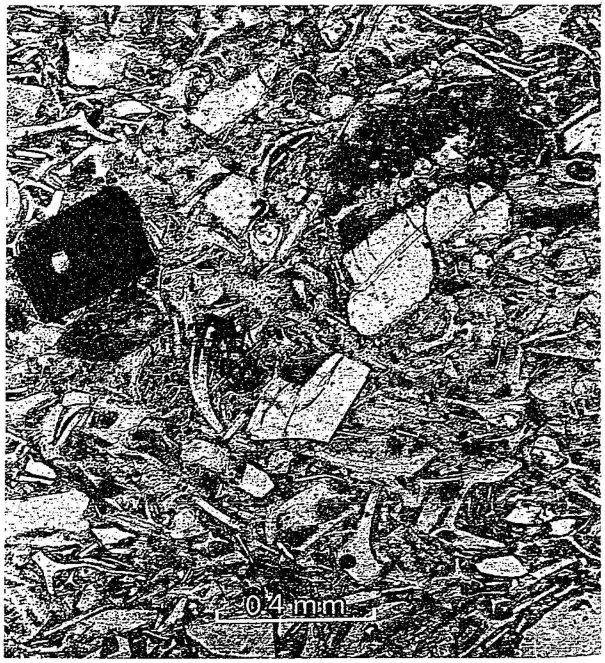

FIGURE 27.—Collected on the road to Sibolga near the waterfall Toroetoing, Lake Toba region, North Sumatra. A glassy tuff with only slight welding and no distortion of the shards.

PHOTOMICROGRAPHS OF WELDED TUFFS FROM PERU AND SUMATRA

Specimens for figures 24 and 25 are from the Arequipa region, Peru, collected by Fenner. These are the type of tuff called sillar by Fenner. Specimens for figures 26 and 27 are from the Lake Toba region, North Sumatra. Collected by N. Wing Easton in 1892 and part of a suite of specimens received from Zeilijlmans V. Emmichoven, and A. L. Simons of the East Indian Geological Survey.

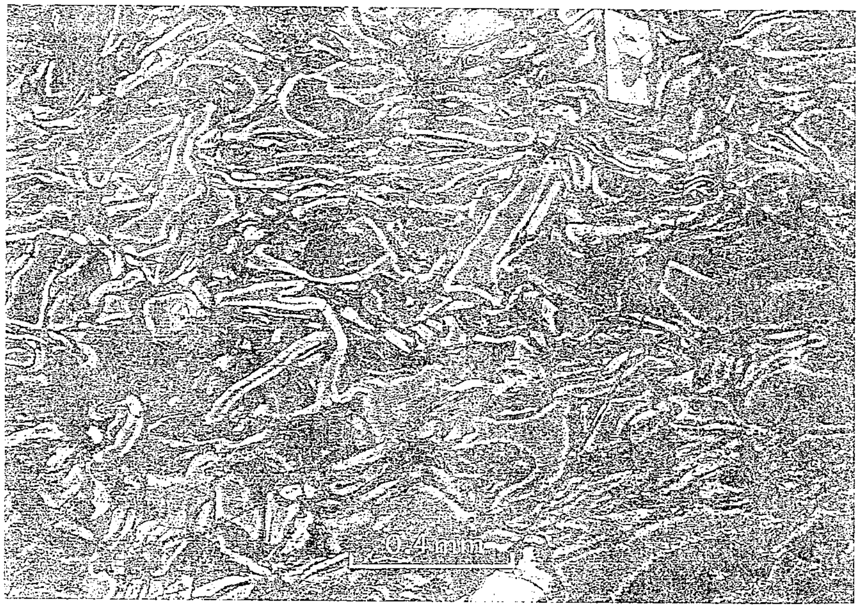

FIGURE 28.—Welded tuff from 40 miles west of Crestone, Saguache County, Colo. The shards are largely glassy, but the narrow white margin marks incipient devitrification, whose materials are too fine to be resolved by the microscope. The shards are only slightly distorted, yet there has been slight plastic yield and very thorough accommodation of each shard to its neighbor. Phenocrysts are sparse.

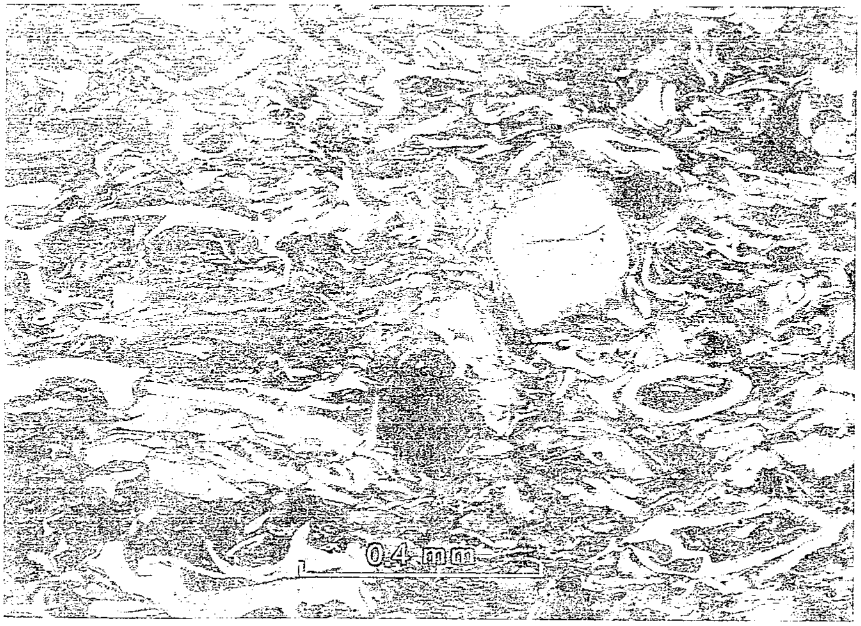

FIGURE 29.—Tuff of the Rattlesnake formation from central Oregon, collected by William T. Pecora, U.S. Geological Survey. The individual shards show slight flattening, due to compression, but uncommonly perfect retention of the primary structure. Many of the unbroken glass bubbles are slightly distorted, and are now oval in outline. The shards are dominantly glassy, but local areas show partial devitrification.

PHOTOMICROGRAPHS OF WELDED TUFFS SHOWING ONLY SLIGHT DISTORTION

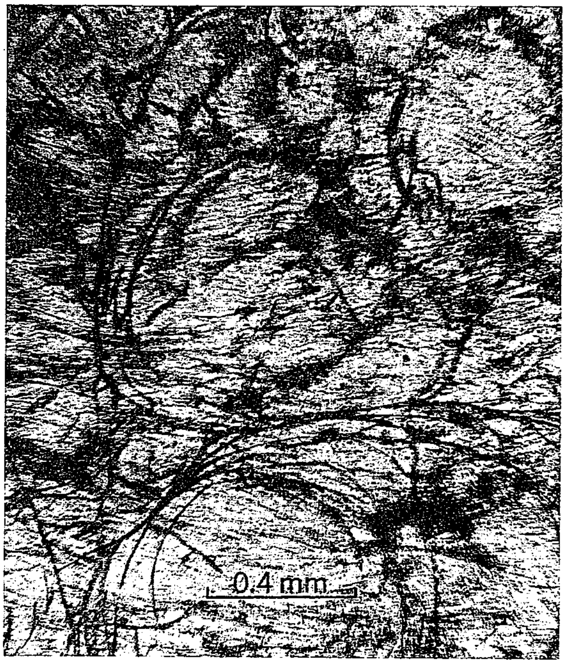

FIGURE 30.—An obsidianlike welded tuff with perlitic cracks. There is only a vague retention of tuff structure, now represented by discontinuous horizontal lines, that suggest, but are not adequate proof of, welded tuff. However, the geologic relations confirm such a derivation.

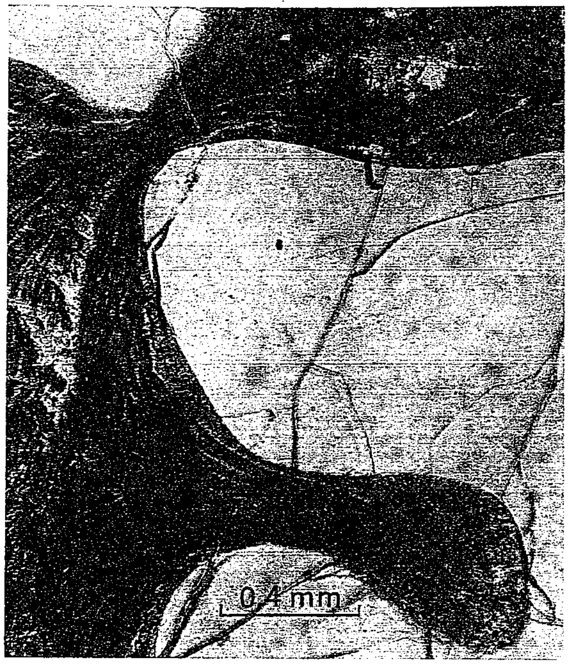

FIGURE 31.—From Jamarillo Creek. Glassy welded tuff showing evidence of plasticity of the glass during welding and extreme distortion. Glass material has been squeezed into a deep embayment in a quartz crystal through an opening about 0.2 mm in diameter.

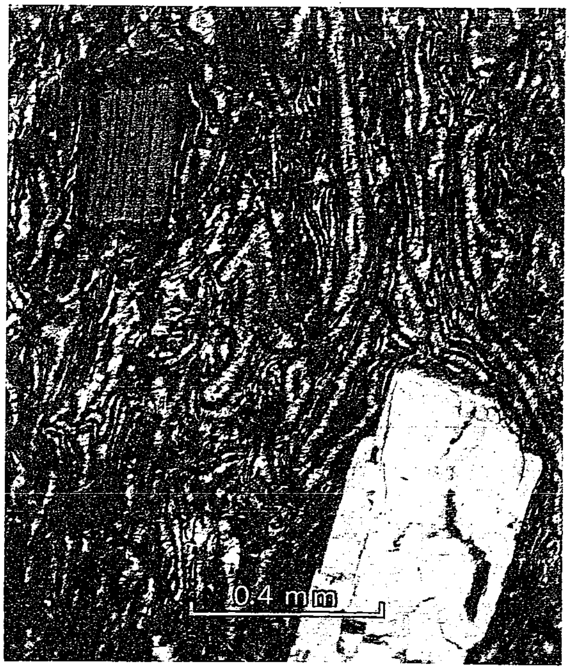

FIGURE 32.—From Leach Canyon near Iron Springs, Utah, collected by J. Hoover Mackin. Thorough welding and strong compression have only slightly impaired the shard structure. Devitrification has followed welding. A nearly euhedral biotite phenocryst lies in the upper left corner and one of plagioclase in the lower right.

FIGURE 33.—Welded tuff from Granite Mountain near Iron Springs, Utah, collected by Ross and Smith. The distortion is similar to that in figure 32, but the specimen in figure 32 is devitrified while this specimen has remained glassy.

PHOTOMICROGRAPHS SHOWING DISTORTION OF WELDED-TUFF STRUCTURES

Specimens for figures 30 and 31 from the Valles Mountains, N. Mex., were collected by Larsen, and Ross and Smith, respectively.

FIGURE 34.—A fine-grained glassy welded tuff showing extreme compression and molding against an embayed plagioclase phenocryst. The shard structure is recognizable, although it simulates the flow structure of an extrusive rhyolite.

FIGURE 35.—Glassy welded tuff from southeastern Idaho, collected by Mansfield. Thoroughly welded tuff with marked compression of the shards, but with good retention of the structure. Note the flattened Y-shaped shard, upper left.

FIGURE 36.—Glassy welded tuff with extreme compression and distortion of the shards. These are molded against the phenocrysts until there is a marked simulation of flow structure, very similar to the specimen shown in figure 37. However, this specimen shows recognizable tuff structures at the extreme right, and a distinct discontinuity of the stretched shards that resemble flow lines. Represents a tuff with abundant phenocrysts.

FIGURE 37.—A glassy flow-banded rock from an intrusive dike, collected by Wilbur Burbank, U.S. Geological Survey, from the Twin Lakes tunnel, Lake County, Colo. Burbank believes that this represents a feeder for the immediately overlying welded tuffs of the area. There is no vesiculation and the flow lines, although nearly distorted, are more continuous than those in figure 36.

PHOTOMICROGRAPHS SHOWING COMPARISON OF WELDED TUFF AND FLOW STRUCTURES

FIGURE 38.—Photomicrograph of welded tuff from the Valles Mountains, N.Mex., collected by Ross and Smith. Well-developed parallel arrangement of the shards in a thoroughly welded tuff is shown. The shards were originally platelike and so the elongation is probably not due to stretching.

FIGURE 39.—Photomicrograph of glassy welded tuff from Lake Toba, northern Sumatra, between Pagaran Psang and Sekanan, along the road from Taroetoeng to Sibolga. Collected by N. Wing Easton, 1892. A thoroughly welded glassy tuff with large pumice fragments that have collapsed and all pore space eliminated, but with a retention of pumice structure. Dark areas represent biotite plates.

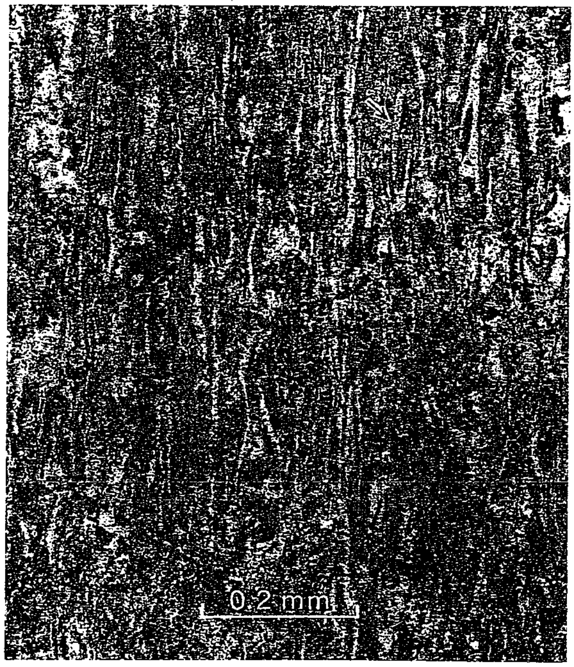

FIGURE 40.—Photomicrograph of devitrified welded tuff that has undergone very marked compression, but retains recognizable shard structure. Just below the upper right corner there is a greatly flattened bubble (marked with an arrow). To the right is a flattened Y-shaped shard.

FIGURE 41.—Photomicrograph of glassy specimen derived from the same welded-tuff horizon as specimen shown in figure 40. Slightly greater stretching has eliminated all clearly recognizable shard structure, and the specimen resembles a flow rock. However, the lenses lack the continuity of typical flow rocks. Compare with figures 34 and 36.

EXTREME DISTORTION OF THE WELDED-TUFF STRUCTURES

Specimens for figures 40 and 41 were collected by J. Hoover Mackin from near Iron Springs, southeastern Utah.

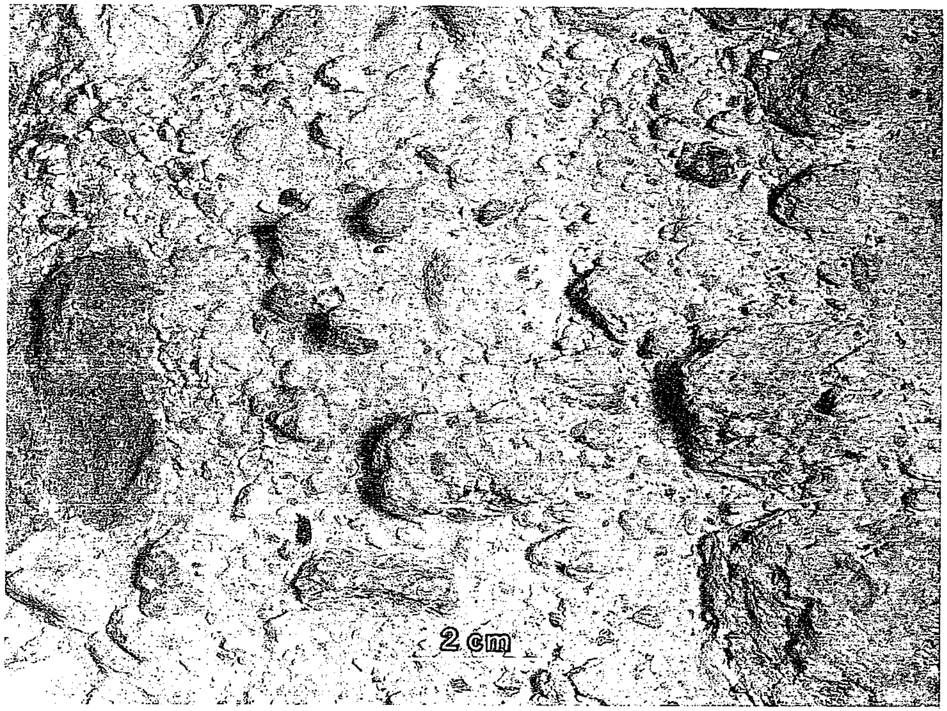

Figure 42.—Photograph of a hand specimen showing nonwelded, uncollapsed pumice fragments that stand in relief on the weathered surface. The pumice retains about 70 percent of pore space. Compare with figure 1, which represents a completely welded horizon from the same flow.

Figure 43.—Photomicrograph of thin section of the same tuff shown in hand specimen in figure 42. Several noncollapsed glassy pumice fragments are shown. The white areas are uncommonly large glass shards. This tuff contains a large proportion of alien rock fragments and crystal grains.

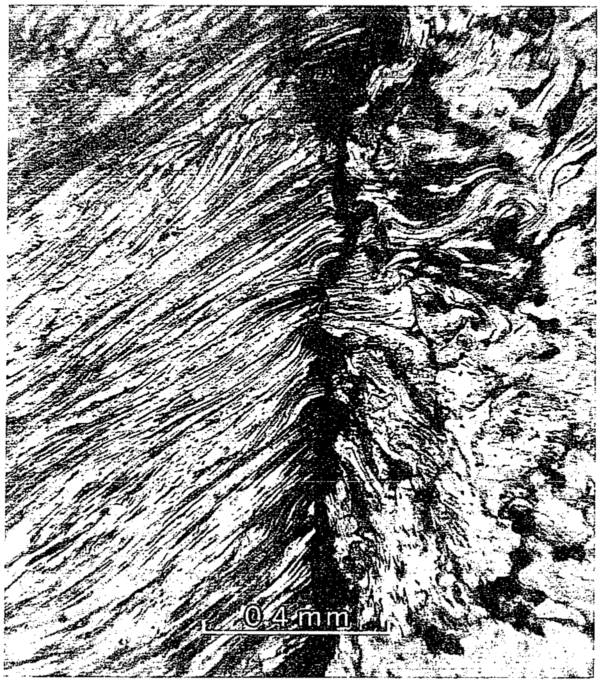

Figure 44.—Photomicrograph of glassy welded tuff from unknown locality in the Western United States. On the right is a thoroughly welded shard structure. On the left is a large pumice fragment in which there has been complete collapse of the pore spaces and welding into a compact glass, but with retention of the pumice structure. Compare with the noncollapsed pumice shown in figure 43.

PUMICE IN ASH-FLOW TUFFS

Specimens shown in figures 42 and 43 are from the basal part of the Battleship Rock ash flow 5 miles north-northeast of Jemez Springs, N.Mex.

FIGURE 45.—Specimen from the Valles Mountains, N.Mex., collected by Ross and Smith. The large light-colored area represents a pumice fragment in which there has been complete collapse and elimination of internal pumice structure, but with traces of the original pumice structure retained in the taillike projection extending toward the lower right corner and molded against a feldspar grain. Compare with the frayed ends of collapsed pumice fragments in figure 18.

FIGURE 46.—A glassy welded tuff from Kuinimi, Kaga, Japan, U.S. National Museum specimen 61728. The left two-thirds of the figure represents ash material, and the right third a pumice fragment. The tuff has been welded into a compact glass and subsequently perlitic fractures have developed. The collapsed pumice structure gives this fragment the appearance of a flow rock.

FIGURE 47.—From Redondo Peak, Valles Mountains, N.Mex. In the lower left corner is an area of welded tuff with much flattened shard structure (diagonal). The pumice that formed the remainder of the figure was much more plastic than the welded shards, and was distorted and molded around the welded-tuff part. The original pore space of the pumice has been completely eliminated but the pumice structure is retained.

FIGURE 48.—From Redondo Peak, Valles Mountains, N.Mex. A large area of pumice that has completely lost its original porosity and has been molded against the quartz phenocrysts and at the same time greatly distorted.

PHOTOMICROGRAPHS SHOWING PLASTICITY OF SHARD AND PUMICE MATERIALS

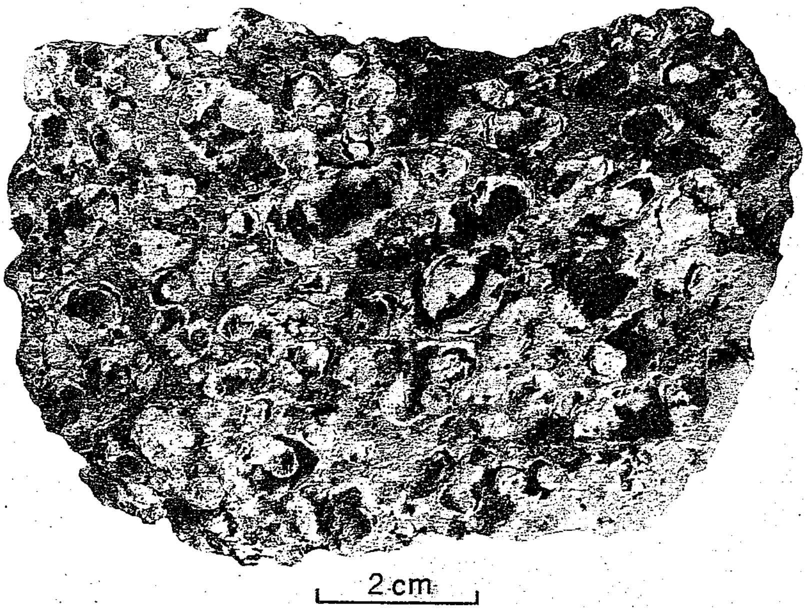

FIGURE 49.—Hand specimen of a ledge-forming facies of the welded tuff that crops out over an extensive area 8 to 10 miles east-southeast of Idaho Falls, Idaho, in the Ammon quadrangle. This facies (6 to 8 ft thick) is everywhere characterized by abundant lithophysal cavities that developed after complete welding and distortion of the shard structures. In this specimen the lithophysae are 2 to 3 cm in diameter. This bed is not recognizable as a welded tuff from field relations, and only by microscopic study is its true character revealed.

FIGURE 50.—Photomicrograph of thin section cut from a dense area in the specimen represented in figure 49. The tuff structure is clearly evident but seems to have been distorted while still plastic by the development of the closely spaced vesicular cavities shown in figure 49.

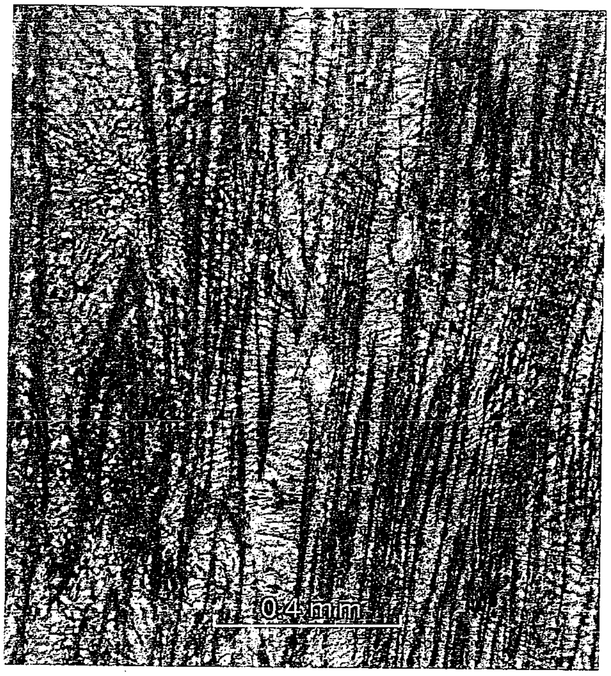

FIGURE 51.—Photomicrograph of thin section of a specimen from the same horizon as figure 49, but collected 8 or 10 miles farther southeast. The vesicles are larger and more elongated (as much as 4 cm) and much more widely spaced. The tuff structure has undergone extreme flattening, but is still recognizable. Note flattened shards that were originally Y shaped. The structure of devitrification products cuts across the shard structure.

DISTORTION OF TUFF STRUCTURE

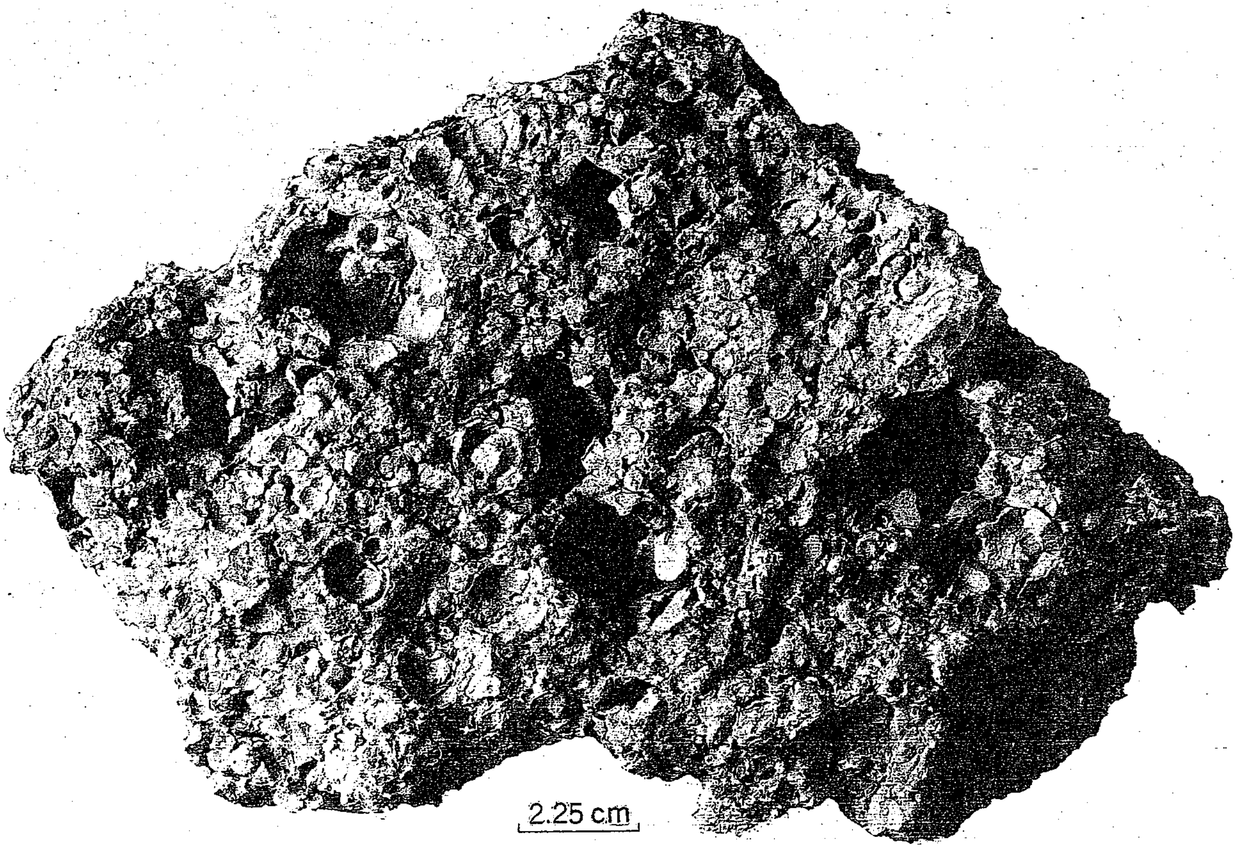

FIGURE 52.—Photograph of a large hand specimen of a welded tuff. The dark areas are vesicular cavities which developed after deposition and complete welding of the tuff. Their presence indicates the ash retained volatiles in solution that were released after welding and during partial devitrification. Two circular areas near the lower left part of the figure show where lithophysae with concentric shell structure have broken out. × 2/3.

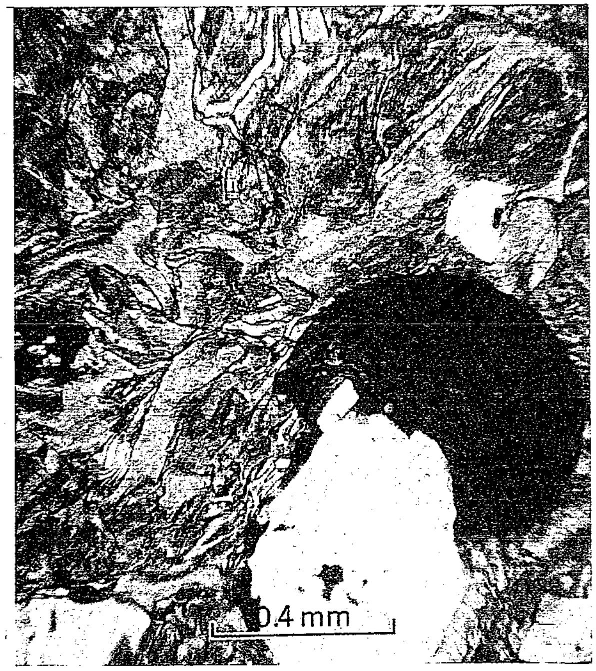

FIGURE 53.—Photomicrograph of thin section cut from the specimen shown in figure 52. The rock is dominantly glassy, but the dark circular area represents a spherulite that has grown out from a plagioclase phenocryst acting as a nucleus. The feldspar-cristobalite intergrowth of the spherulite is not actually dark colored, but appears dark in the photograph because of the very strong dispersion of light resulting from the fine-grained intergrowth of materials with very different mean indices of refraction (K-Na feldspar = 1.524, cristobalite = 1.486).

FIGURE 54.—Photomicrograph of part of a very large spherulite. The differences in the devitrification products have caused three distinct concentric zones. The inner zone seems almost black because of the very marked dispersal of transmitted light. Outside of that is a lighter zone where the ash-shard structure is observable, but it also shows in the third and outer zone.

SPHERULITES AND LITHOPHYSAE SPECIMENS

Collected by Mansfield in southeastern Idaho.

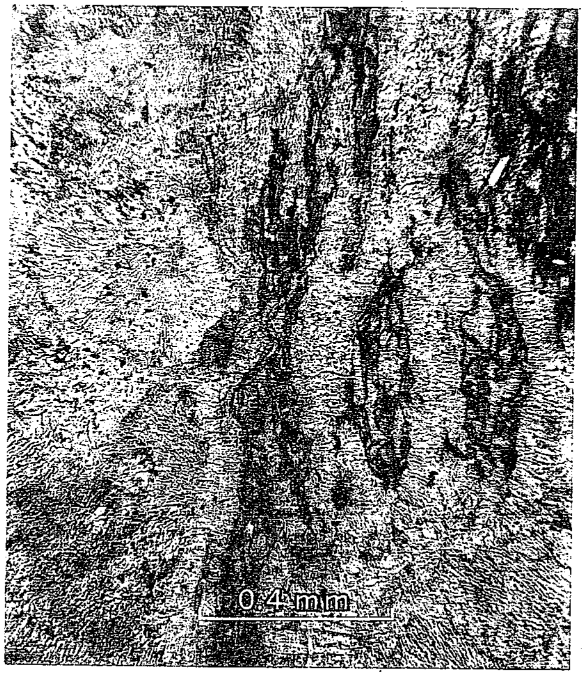

FIGURE 55.—Specimen collected half a mile south of Sulphur Springs, Jemez Springs quadrangle, Valles Mountains volcanic region, New Mexico, by Ross and Smith. The dark areas retain the shard structures, but in the lighter areas radial aggregates of feldspar and cristobalite have developed and completely destroyed the shard structure. The left third of the figure represents a large pumice fragment.

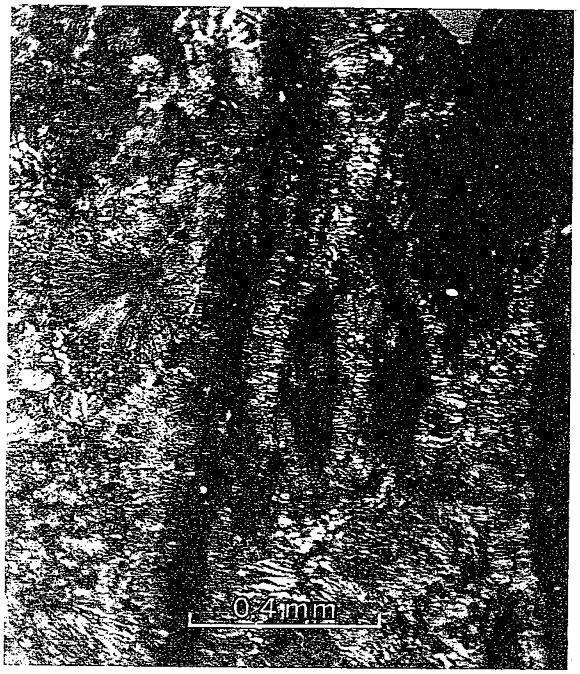

FIGURE 56.—The same area shown in figure 55, but under crossed nicols. This shows the coarse-grained intergrowth of feldspar and cristobalite in areas that have lost their shard structure (light) and the much finer structure in those areas where the structure has been retained (dark).

FIGURE 57.—A large pumice fragment imbedded in shard material in which the structure is still recognizable. The devitrification of the pumice grains has destroyed the original fibrous structure. Specimen collected by Ross and Smith, Valles Mountains, N.Mex.

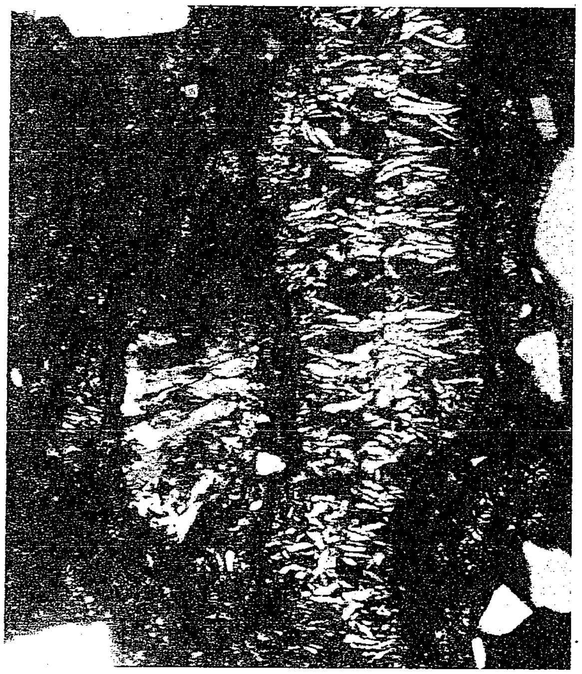

FIGURE 58.—The same area shown in figure 57, but under crossed nicols. This shows the tendency, observable in almost all welded tuffs, for coarse-grained devitrification products (feldspar and cristobalite) to develop in the pumice fragments; and much finer grained ones in the shards.

PHOTOMICROGRAPHS SHOWING DEVITRIFICATION OF PUMICE

FIGURE 59.—Welded tuff that has undergone welding and extreme distortion of the still-recognizable shard structures.

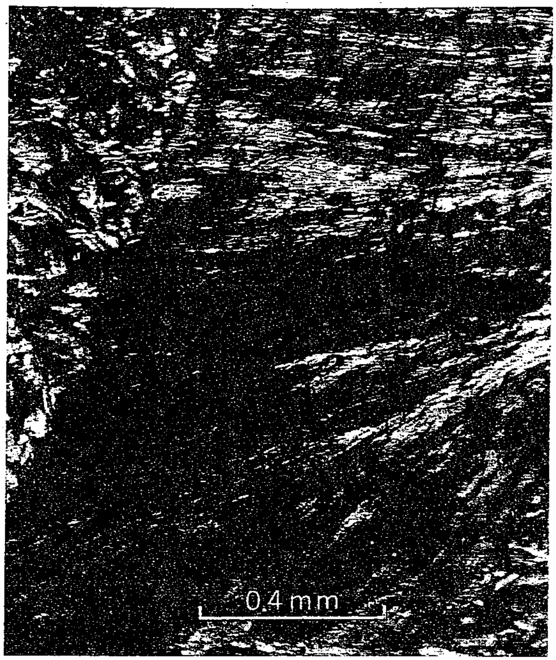

FIGURE 60.—Same area as illustrated in figure 59, but under crossed nicols. This shows a coarse-grained radial aggregate of feldspar and cristobalite laths which have developed independently of the original shard structure.

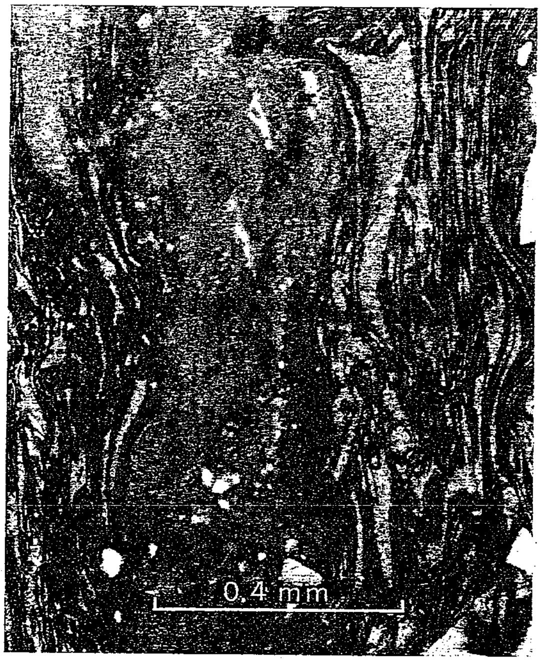

FIGURE 61.—Welded tuff from southeastern Idaho, collected by Mansfield. All the shards are devitrified, but the light area represents a pumice fragment in which coarser grained intergrowth of cristobalite and feldspar has developed and where the pumice structure has been partly destroyed.

FIGURE 62.—Welded tuff from Redondo Peak, Jemez Springs quadrangle, Valles Mountains, N.Mex., collected by Ross and Smith. Welding and extreme flattening of the ash structure is represented at the extreme right. In the central part of the figure (white) the development of uncommonly coarse grained devitrification products has completely destroyed the original structure. If the entire rock had undergone the same loss of structure, evidence of derivation from a tuff would be lost.

PHOTOMICROGRAPHS SHOWING DESTRUCTION OF STRUCTURE BY DEVITRIFICATION

Specimens for figures 59 and 60 were collected by Ross and Smith from the Valles Mountains, N.Mex.

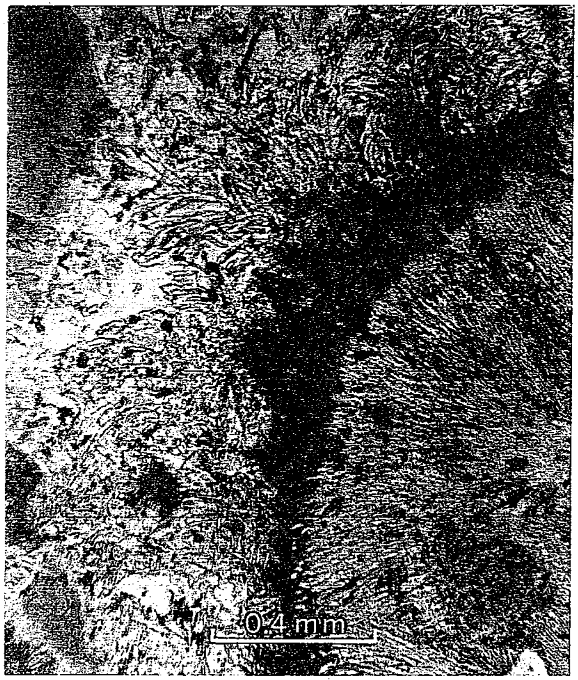

FIGURE 63.—Welded tuff from the Valles Mountains, N.Mex., collected by Ross and Smith, showing a very large spherulite in which the radial aggregates of feldspar and cristobalite are well represented. At the left the secondary minerals have developed a plumose structure. All direct evidence of tuff structure has been destroyed.

FIGURE 64.—Welded tuff from the Valles Mountains, N.Mex., showing the development of groups of spherulites, with concentric banding due to variations in grain size of the aggregates of cristobalite and feldspar.

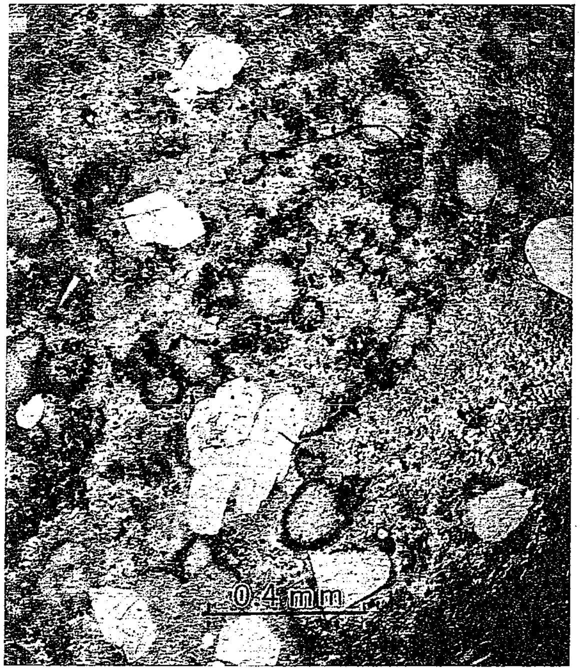

FIGURE 65.—Welded tuff from the Lake Toba region, Sumatra, showing spherulitic areas developed in a welded tuff.

FIGURE 66.—Welded tuff from the Valles Mountains, N.Mex., collected by Ross and Smith. An open cavity in a welded tuff in which platelike crystals of tridymite have developed.

PHOTOMICROGRAPHS OF DEVITRIFICATION MATERIALS

Figures 63, 64, and 65 illustrate the complete destruction of the original tuff structure.

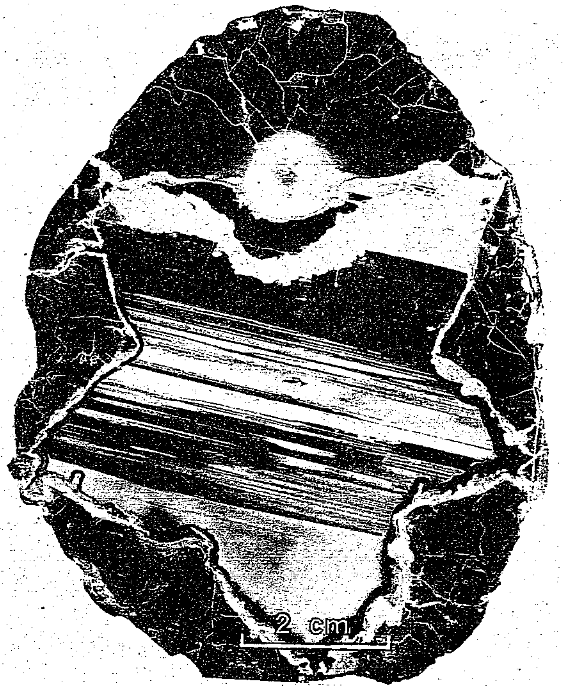

FIGURE 67.—Photograph of a polished section through a so-called thunder egg that represents a type of hollow spherulite which commonly develops in glassy volcanic rocks. Volatiles originally in solution in the glass collect at the center during the development of anhydrous minerals which form the gray border—the material shown in figures 68 and 69. The originally hollow central part was subsequently filled with chalcedony. × 1.

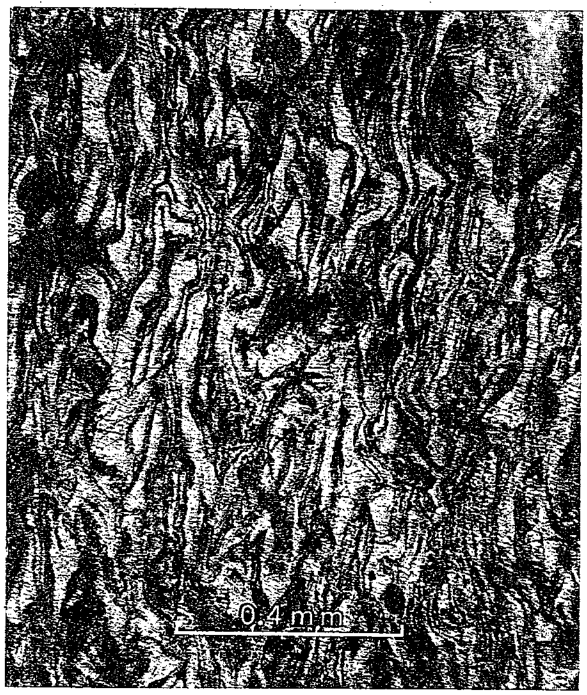

FIGURE 68.—Photomicrograph of the outer rim material of figure 67. The section represented in this figure was cut perpendicular to the plane of deposition.

FIGURE 69.—Photomicrograph of the outer rim material of figure 67. The section represented in this figure was cut parallel to the plane of deposition. Figure 68 and this figure shows the marked difference in flattening and distortion of the shard structure in the two planes; in both planes the shard structures are well preserved. Compaction and welding was complete before devitrification and the parallel growth of feldspar and cristobalite (diagonal structure in this figure) developed independently of the original shard structure. Compare with shards in figures 71–74, in which the development of feldspar and cristobalite started at the grain boundary of each shard.

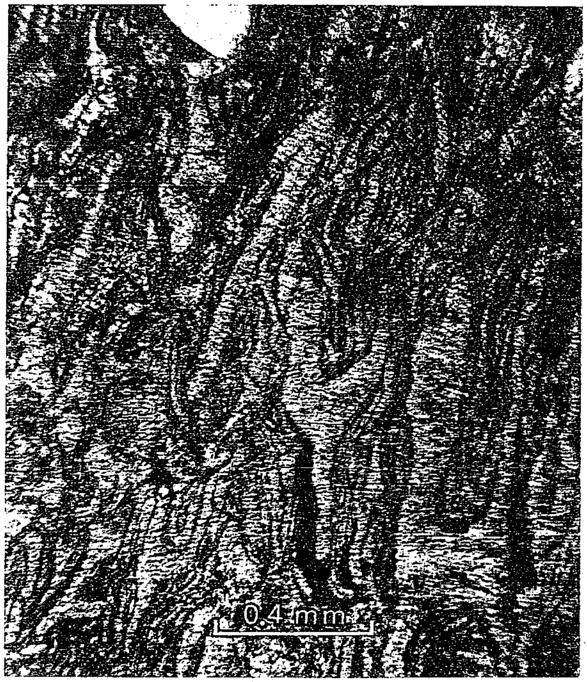

FIGURE 70.—Photomicrograph of welded tuff from southeastern Idaho, collected by Mansfield. The larger shards seem to have undergone very little distortion, but the others are molded against them giving a marked parallel structure. Welding was complete before devitrification and the feldspar-cristobalite formed parallel aggregates cutting across the shard structure (horizontal).

DEVITRIFICATION CHARACTERISTICS

Figures 67, 68, and 69 represent material from central Oregon, collected by Gen. J. S. Hatcher. U.S. Army, retired.

FIGURE 71.—Thin section of tuff showing welding and devitrification, but without distortion of the shard structure.

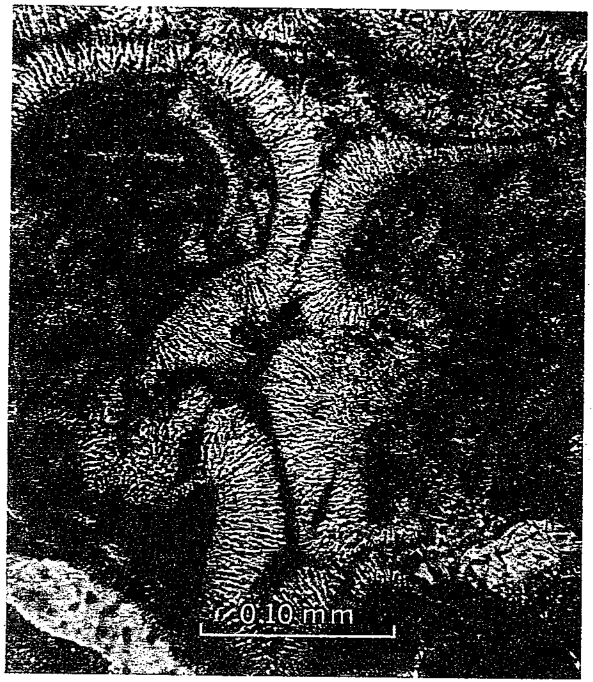

FIGURE 72.—An area from thin section shown in figure 71 under high magnification. The parallel intergrowth of feldspar and cristobalite (axiolitic structure) is well represented. The large shard fragment represents the walls of several bubbies.

FIGURE 73.—Devitrified welded tuff. Most of the thin section shows little distortion of the original shard structure, but at the right side of the figure there is marked molding of the shards around a feldspar phenocryst (white).

FIGURE 74.—Devitrified welded tuff from an unknown locality in the Western United States showing uncommonly perfect axiolitic structure. Although the devitrification products (feldspar and cristobalite) are uncommonly coarse grained, the original forms of the shards are perfectly retained.

PHOTOMICROGRAPHS OF WELDED TUFFS SHOWING AXIOLITIC STRUCTURE

Specimens for figures 71, 72, and 73 are from the Valles Mountains, N.Mex.; collected by Ross and Smith. Axiolitic structure is the result of crystal growths, beginning at the shard boundaries, and meeting at a line of discontinuity (dark central line). The high relief is due to the large difference in index of refraction of the devitrification products—cristobalite and feldspar. Compare with figure 95 which is a reproduction of a sketch by Zirkel illustrating the structure he named "axiolitic."

FIGURE 75.—Welded tuff from Australia, collected by Richards and Bryan (1934). The shard structure is discernible, although it has been partly obscured by devitrification. Other specimens from the Brisbane tuffs show even greater loss of structure.

FIGURE 76.—Devitrified welded tuff from Glashutte, Schermitz, Hungary; U.S. National Museum specimen 36270. The shard structures are obscured, but not entirely lost. An euhedral, high-temperature quartz phenocryst is near the bottom.

FIGURE 77.—Devitrified welded tuff from Pusan, Korea, collected by Allen Nicol, U.S. Geological Survey. The shard structure is only dimly retained, but axiolitic structures are observable at the left.

FIGURE 78.—Thin section from an old German collection of slides, which was marked as representing a rock from Elfdalen Daloria, Sweden. Hjelmqvist states that these welded tuffs are sub-Jotnian (sub-Keweenawan) in age. The shard structure has undergone stretching so that parts of the thin section are indistinguishable from a flow rock, but, locally, shard structures are preserved.

PHOTOMICROGRAPHS OF WELDED TUFFS FROM FOREIGN LOCALITIES

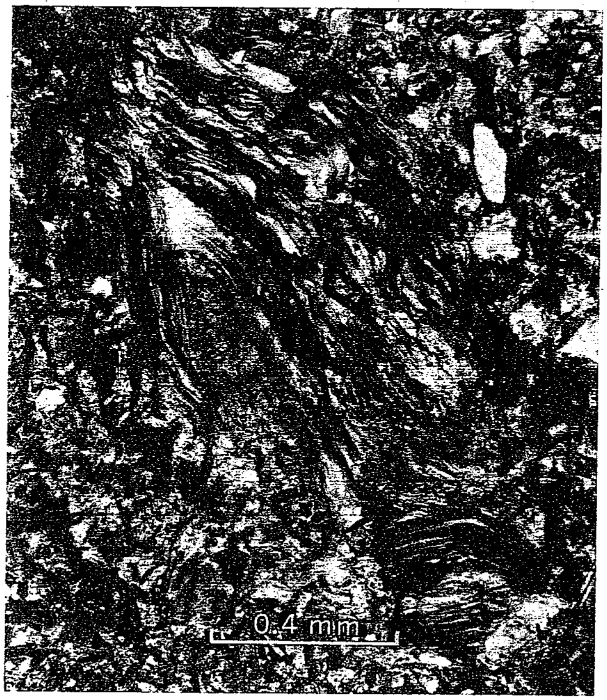

FIGURE 79.—A large glassy pumice fragment imbedded in shards (lower left). Welding is slight, but the pumice fragment seems to have undergone distortion.

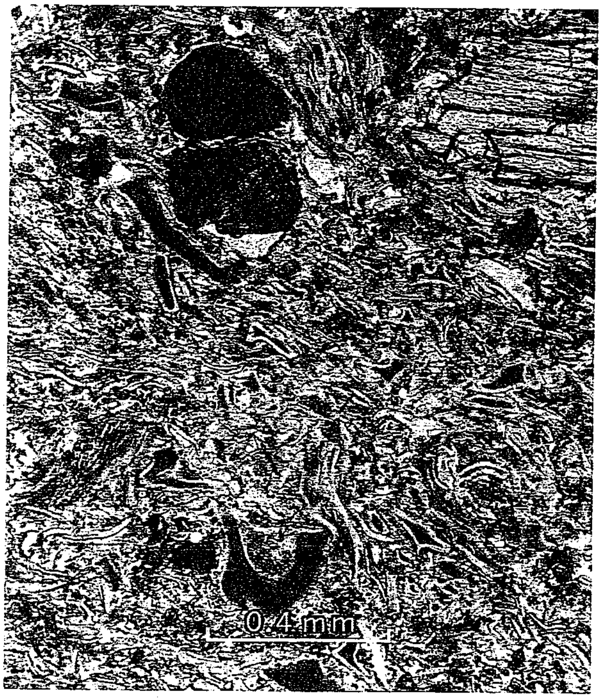

FIGURE 80.—Fine-grained andesitic tuff. Welding is moderate but there has been warping and accommodation of shards to one another. The slide shows many rock fragments and crystals derived from an earlier andesitic rock. The large crystal (upper right) is augite.

FIGURE 81.—Andesitic welded tuff from Aso caldera, Kyusyu, Japan, collected by C. G. Johnson, U.S. Geological Survey. A thoroughly welded tuff, with abundant andesitic phenocrysts and rock fragments. Augite crystals lie near the center and lower right corner; an euhedral plagioclase crystal is near the lower left.

FIGURE 82.—Welded tuff from near McKays, Calaveras County, Calif., collected by Smith. Illustrates the type of biotite-augite latite described by Ransome. The tuff structure is poorly preserved. This specimen represents a welded tuff uncommonly rich in crystal fragments. Some of these materials represent fragments derived from older andesitic rocks.

PHOTOMICROGRAPHS OF WELDED TUFFS OF INTERMEDIATE COMPOSITION

Figures 79 and 80 are from Erevan, Russian Armenia; U.S. National Museum specimen 52079.

FIGURE 83.—Photomicrograph of specimen collected from the bank of the Malargue River at La Valenciana Mendoza, Argentina, by F. G. Bonorino, and described by him as andesite. The thin section was cut parallel to the plane of deposition.

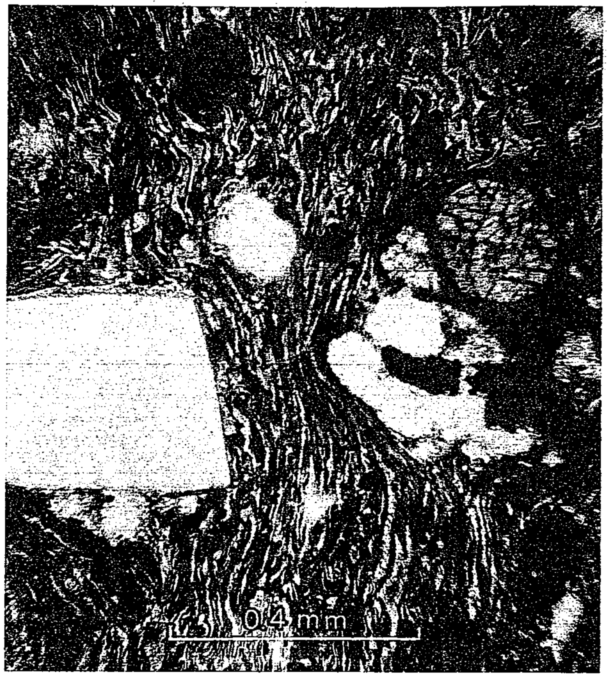

FIGURE 84.—Photomicrograph of a thin section cut from the same specimen as figure 83, but perpendicular to the plane of deposition. Note the greater flattening of the structure.

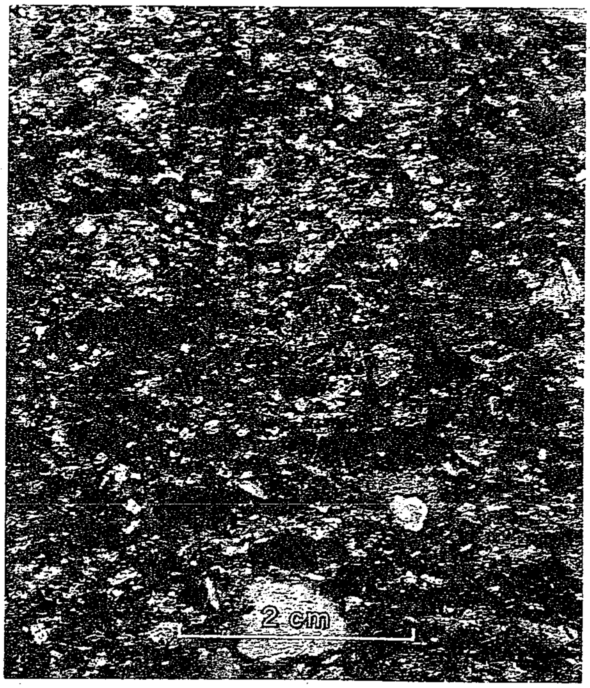

FIGURE 85.—Photograph of a hand specimen. The black areas represent the larger pumice fragments which have collapsed, and lost the original pumice structure. × 1½.

FIGURE 86.—Photomicrograph of a thin sction of specimen shown in figure 85. The dark lenses represent pumice fragments in which the original pumice structure has been largely destroyed.

ANDESITIC WELDED TUFFS

The tuff shown in figures 83 and 84 is glassy and shows very complete welding and marked flattening of the shard structure. A large proportion of the crystal and rock fragments represent alien materials. The specimen for figures 85 and 86 illustrates andesitic welded tuffs from Costa Rica, collected by Gabriel Dengo, from the Nuestro Amo power plant, Virilla River.

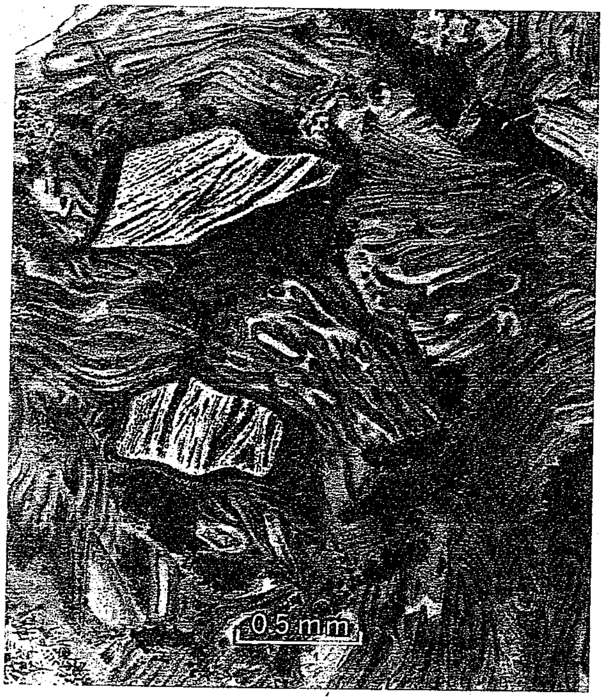

FIGURE 87.—Photographic reproduction of a colored drawing by Iddings (1885–86, pl. 16, fig. 2). While this is not a welded tuff it is presented as a part of the development of Iddings' concept of welded pumice.

FIGURE 88.—Photomicrograph of one of Iddings' thin sections of rocks from Yellowstone National Park. This evidently represents the same material shown in figure 87, but may not have been the same thin section used by Iddings for the drawing shown in figure 87.

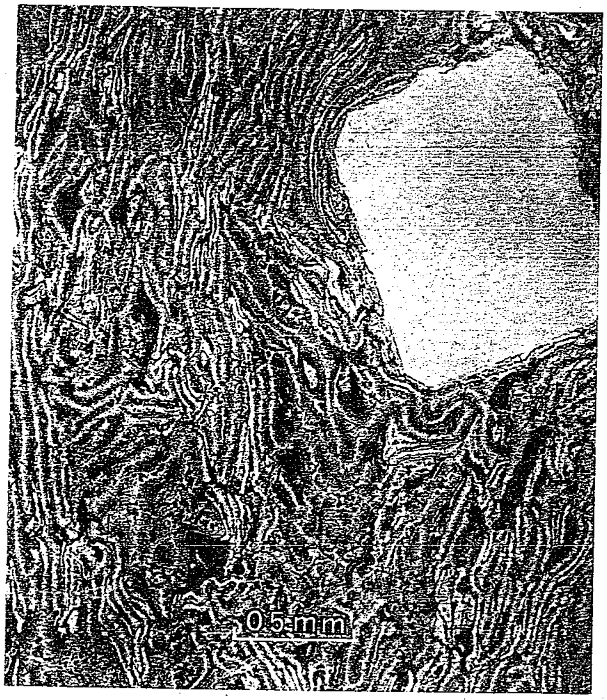

FIGURE 89.—Photomicrograph slightly enlarged and copied from an illustration from Iddings' study (1899, pl. 50, fig. 100) of rhyolitic rocks from Yellowstone National Park. The illustration is also shown in another report by Iddings (1909, fig. 22, p. 332) and bears the title "Welded pumice with axiolites." This illustration is an uncommonly good representation of an ash-flow tuff that has undergone complete welding, some distortion of the shards, molding against the quartz phenocryst, and devitrification; all with good retention of the shard structure.

FIGURE 90.—Photomicrograph of a thin section from a group of specimens collected in the Valles Mountains, N.Mex., by Holmes and Powell and turned over to Iddings for study. The specimen from which this thin section was cut was described as "from the cliff overlooking Jemez Springs," and is from the same region now under study by the authors.

ILLUSTRATIONS SHOWING SOME OF THE ORIGINAL MATERIAL DESCRIBED BY IDDINGS AS WELDED PUMICE

Figures 87 and 88 are from Obsidian Cliff, Yellowstone National Park, and represent some of the material called welded pumice by Iddings. This is evidently a brecciated and rewelded pumice from a rhyolitic lava flow.

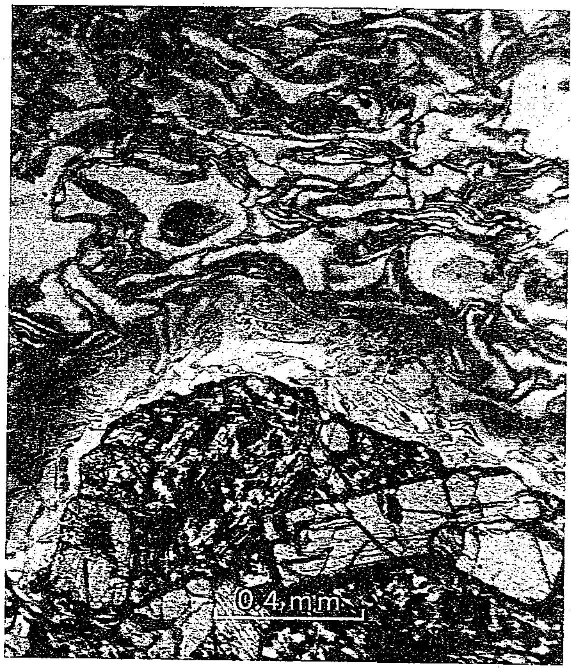

FIGURE 91.—Welded tuff from Fall River basin, west slope of mountain north of the head of Conant Creek (Iddings, 1899, p. 378; specimen 1958). Glassy welded tuff with a large inclusion of andesite that seems to be typical of the Yellowstone National Park welded tuffs.

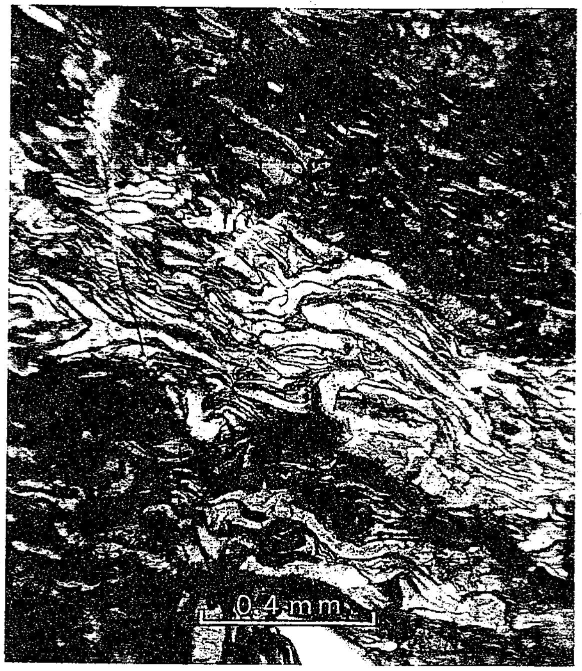

FIGURE 92.—Iddings' thin section 2150, not described by him. It belongs to a group from the northeastern corner of Yellowstone National Park. The dark part shows incipient devitrification and the light part is glassy. Thorough welding and slight distortion of the shards is evident.

FIGURE 93.—Zirkel collection, specimen 22297; U.S. National Museum specimen 350. Locality described as "southeast from Wadsworth, Nevada." Glassy welded tuff. Near the left margin there is bleaching of the outer borders of the shards. The platelike character indicates that the thin section was cut diagonally to the plane of deposition.

FIGURE 94.—Zirkel collection, specimen 21834; U.S. National Museum specimen 499. Locality described as "Mopung Hills, W. Humboldt, Nevada." The figure shows extreme flattening and stretching, but with good evidence of shard structures. The lenses show marked discontinuity, and in many places there are nearly parallel branches of a lens, due to flattening of a Y-shaped shard. Areas where very flat lenses are folded back upon themselves is a characteristic of much-compressed welded tuffs.

PHOTOMICROGRAPHS OF WELDED TUFFS OF HISTORIC INTEREST

Figures 91 and 92 are from Iddings' original set of thin sections of "pumice tuffs" from Yellowstone National Park. Figures 93 and 94 are reproduced from a very large collection of rocks studied by Zirkel as a part of the 40th Parallel Report; a large proportion of this collection proved to be welded tuffs, and so these thin sections made about 80 years ago have now provided new evidence of the abundance of welded tuffs in the Basin and Range region.

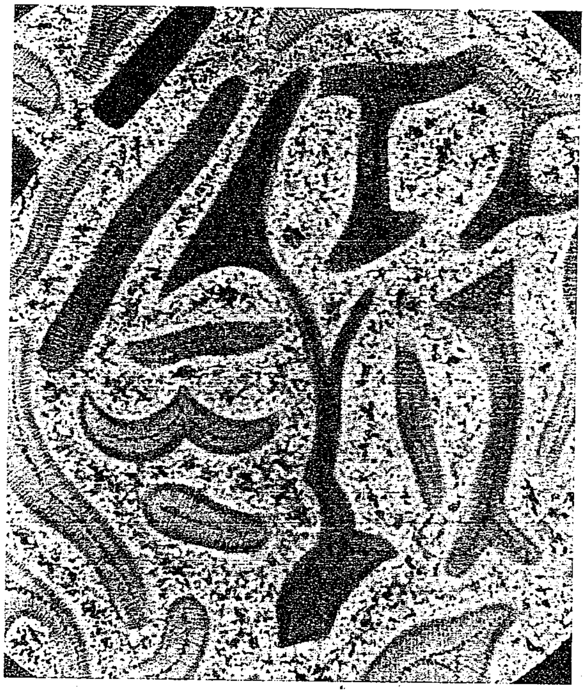

FIGURE 95.—Photographic reproduction of a drawing presented by Zirkel (1876, pl. 7, fig. 4). Zirkel did not recognize the full significance of the welded tuffs he observed, but this illustration shows that he recognized the essential petrographic characteristics. The parallel intergrowths of feldspar and cristobalite, for which he proposed the name "axiolitic" are well illustrated. Compare with these structures shown in figures 87–90.

FIGURE 96.—Photomicrograph of ash-flow tuff from the Valley of Ten Thousand Smokes, collected by Zies. Specimens of these tuffs available to the authors are nonwelded, but platelike shards which were bent against phenocrysts have been observed. Little induration is shown and the porosity is high. There is a wide range in size of materials, with dust, shards, and pumice fragments (extreme right) all present. A circular unbroken glass bubble lies near the center and another near the upper right corner. In the upper part of the figure there is a large irregularly shaped glass shard.

FIGURE 97.—Photomicrograph of welded tuff from Taupiri Gap, Waikato River, North Island, New Zealand, collected by Ross. This represents the materials which were the basis for Marshall's (1935) outstanding contribution to an understanding of ash-flow tuffs. This tuff is welded and devitrified, and there has been dimming by devitrification, but little distortion of the tuff structure. The new Zealand tuffs contain abundant phenocrysts of feldspar and quartz.

FIGURE 98.—Photomicrograph of thin section of a welded and devitrified tuff cut from one of several specimens submitted by Jean Bouladon. These specimens were collected by Bouladon and Jouravsky, and described by them (1954), from the Anti-Atlas region of Morocco. Their description represents the first recorded recognition of a welded tuff of Precambrian age. As can be seen from this thin section, the structure is remarkably good and traces of the axiolitic structure are recognizable. Compare with this structure in figures 71–74.

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Zones and Zonal Variations in Welded Ash Flows

By ROBERT L. SMITH

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 354-F

A concept of zonation in ash flows
based on degree of welding and
type of crystallization

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1960

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

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21. Zones of no welding, partial welding, and dense welding, and their approximate crystalline equivalents Facing page 152

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

ZONES AND ZONAL VARIATIONS IN WELDED ASH FLOWS

By Robert L. Smith

ABSTRACT

Welded tuffs are recognized as special parts of ash flows, er pyroclastic flows, or, more rarely, air-fall deposits. Ash ows may be emplaced at any temperature below a maximum ption temperature. Those emplaced above a minimum lding temperature may show any and all degrees of welding d crystallization.

Three basic zones are recognized, the *zones of no welding, artial welding,* and *dense welding.* In sheets where the zone dense welding occurs, the zones of no welding and partial lding will have upper and lower counterparts.

Cooling of welded ash flows may result in sheets that range m completely glassy (except for phenocrysts and inclusions) mostly crystalline.

Crystallization superimposed on the zonal patterns produced welding results in another set of zones that is controlled in art by degree of welding.

Three principal types of crystallization that take place dur- the cooling history are recognized. These in order of fre- ncy of occurrence, are devitrification, vapor-phase crystal- ation, and granophyric crystallization. The *zone of devitrification* is common to most crystallized welded tuffs and fre- ntly occupies most of the zones of dense welding and partial lding. The *zone of vapor-phase crystallization,* where pres- , occupies the porous parts of the welded tuff sheets and ches its maximum development in the upper zone of partial elding where it overlaps the zone of devitrification. The *e of granophyric crystallization* is probably confined to cool- units several hundreds of feet thick where it will divide e devitrified zone into upper and lower parts. Fumarolic ration may be found in the upper zone of no welding.

Single ash flows may cool with the formation of a basic tern of zones. This pattern is illustrated and described h for those sheets which remain glassy and for those in ich crystallization has occurred. These flows are called *ple cooling units.*

Successive ash flows, emplaced quickly enough to bridge the ling gap between flows, will form a stack of flows that may o cool to form the zonal pattern of a simple cooling unit. e gaps or hiatuses, here called partings, may contain or sist of lump pumice layers, flow surfaces reworked by wind water, airfall pyroclastic material, other deposits, or minor sional unconformities.

Compound cooling units consist of multiple flow units with without visible partings and which show zonal patterns t depart from the patterns of the simple cooling units. Horizontal separation of compound cooling units into separate cooling units suggests the existence of a hypothetical unit, the *composite sheet,* which could have time-stratigraphic significance.

Buried topography can have a profound influence on the zonation of certain ash-flow cooling units. Very hot ones, because of their high compactability potential, will show less zonal change than colder ones, although they will show greater surface expression of the buried topography. Abrupt changes in relief, especially if the buried topographic high rises to the top of the zone of dense welding, can cause horizontal changes, in a short distance, that may be difficult to interpret.

INTRODUCTION

In this report, welded tuffs are considered to be special parts of ash flows, other pyroclastic flows, or more rarely, air-fall deposits (not to be confused with fused tuffs, p. 155). Most students of welded tuffs have recognized vertical variations of texture, specific gravity, color, mineralogy, and other properties within the deposits. Horizontal variations are rarely emphasized because complete ash-flow sheets have not been mapped, particularly in detail. Mapping of complete sheets has not been done because of the generally large areal extent of the sheets, they may be of only casual interest to the mapping problem, or because erosion, and cover by younger rocks, limits their area of exposure.

The uniform and unsorted character of ash-flow deposits has been cited as a criterion for their recognition. Although this is generally true, the complex emplacement and cooling history of many such deposits may produce various textural and mineralogical facies that bear little or no resemblance to the original materials of the ash flows. These variations are zonal and normally show a consistent pattern of transitions both vertically and horizontally in uniform ash flows which have had an unimpeded cooling history. Once this zonal pattern is clearly understood for simple cooling units, progress can be made in interpreting aberrant patterns in more complex deposits.

The purpose of this report is to describe the zones and the simple zonal patterns by means of 4 simplified diagrams (pl. 20 *A–D*) and a brief text. The diagrams are not intended to represent specific welded ash flows but are simply hypothetical models. They were constructed to illustrate, in part, the writer's concept of simple ash-flow cooling units. The scales used give an order-of-magnitude relation among the different zones that is probably realistic for some natural sheets. The most difficult characteristics to generalize are the horizontal changes, because a cooling unit may range from less than a mile to many tens of miles in length, or from less than a square mile to hundreds and perhaps thousands of square miles in area. The true nature of the distal ends is generally problematical. They are rarely preserved or recognized in prehistoric sheets and there appears to be a wide variation in historic "nuée ardente" deposits, from "snub noses" to thin tapered ends often measurable in inches.

The diagrams were constructed based on the assumption that some cooling took place in the direction of thinning. Although this is probably a common condition it is by no means necessarily true for all flows. Some widespread ash-flow cooling units show only slight effect of cooling or thinning over tens of miles whereas others show marked effects in only a few miles. The direction of thinning may be related to the surface underlying the flow or it may reflect a change away from the source area. These facts, among others, indicate the need for a critical examination of accepted concepts on the mechanics of eruption and emplacement of ash flows.

The use of welded tuffs for correlation purposes presents many pitfalls to the geologist, but with careful work a high degree of success should be achieved. The potential importance of these rocks as stratigraphic marker beds cannot be overemphasized, considering their possible long-distance continuity in terrane where lensing and facies changes, in sedimentary and other volcanic deposits, are common.

The presentation of hypothetical diagrams without documentation leaves much to be desired. Also much of this report may seem academic concerning very young and undeformed welded ash flows. However, this study should have practical merit where applied to mapping and interpreting problems in highly deformed areas. It should also be useful in regions where ash-flow sheets from different sources overlap, and in the vicinity of some ore deposits where the geologist must locate relative spatial position within a rock body. In the vicinity of most ore deposits, alteration of different types will further complicate matters, but this difficulty may be overcome if the geologist has a clear understanding of the normal characteristics of the unaltered rocks. The zonal patterns will be extremely important for detailed geochemical studies.

ACKNOWLEDGMENTS

The writer is indebted to Clarence S. Ross with whom he has studied welded tuffs for many years and with whom he has written a more comprehensive report (Ross and Smith, 1960). Much of the material in the present report is an outgrowth of this earlier study, although the writer is solely responsible for the organization of the data and theory as presented here. The writer is especially indebted to Roy A. Bailey, also a close working companion of many years, who has been a most helpful critic. Of the many other Geological Survey colleagues who have aided the writer's studies special thanks are due C. A. Anderson and Harry W. Smedes for their constructive criticisms.

ERUPTION AND EMPLACEMENT

Much could be written about the eruption of pyroclastic materials that are emplaced as hot sheetlike bodies and whose slow cooling may result in deposits that show striking physical and chemical differences from the initially erupted material. However, the main purpose of this report is to discuss the more obvious characteristics of the deposits after they have cooled. It is well recognized that these deposits were, for the most part, emplaced as hot avalanchelike masses or particulate flows, many if not all of which contained hot gas and many of which were autoexplosive. The evidence for flowage as the principal mechanism for emplacement of these deposits has been cited by many authors; the most fundamental papers are those by Fenner (1923), Marshall (1935), and Gilbert (1938). In the present report, the basic unit of most of these deposits is referred to as an ash flow.

Ash flows can probably be emplaced at any temperature below a maximum eruption temperature. However, there will be a temperature of emplacement below which no visible physical or chemical changes will take place during cooling. This temperature may be referred to as the minimum welding temperature and will vary from place to place with changes in the variables that control the lower limit of the softening range of the glass.

Nonwelded ash flows are important, but those emplaced at temperatures above their minimum welding temperatures are of greater interest.

A single ash flow may be the only unit of cooling, or two or more ash flows, with or without intercalated air-fall beds or other partings, may combine to form the cooling unit. A deposit that can be shown to be a *cooling unit* in one place, may by division horizontally, become two or more cooling units, separated by chill zones, air-fall pyroclastic rocks, sedimentary deposits, erosional unconformities, or lava flows. The writer will refer to this complex rock body as the *composite sheet.* The complexities inherent in such a scheme are infinite and the geologic implications will be obvious.

WELDING

The welding process must begin immediately after emplacement if the ash flow or any part of it, comes to rest above its minimum welding temperature. Welding continues until it is complete or until the process is stopped by cooling or crystallization of the glass.

In the present report welding is briefly defined as that process which promotes the union or cohesion of glassy fragments. The degree of welding may range from incipient stages marked by the sticking together or cohesion of glassy fragments at their points of contact and within the softening range of the glass to complete welding marked by the cohesion of the surfaces of glassy fragments accompanied by their deformation and the elimination of pore space, and perhaps ultimate homogenization of the glass.

Incipient welding may be recognized in some very young and fresh glassy tuffs by brittle rather than crumbly fracture, although the rock is very porous. However, this criterion is not entirely dependable because other types of induration may cause the rock to break in a similar manner.

Where the distinction between nonwelded and incipiently welded tuff is necessary, the boundary should be placed at, or close to, that point where deformation of glassy fragments becomes visible. Deformation of pumiceous fragments and shards is the only positive criterion of welding in the tuffs which have crystallized, particularly in older rocks.

Incipient welding presumably takes place in most welded tuffs before the deformation of glass fragments becomes visible, because the deformation accompanying welding is related primarily to lithostatic load pressure, especially at the lower temperatures. In practice the transition between visible deformation and obviously nonwelded tuff can be located in most tuffs within a few feet or at most a few tens of feet.

Even the sillars (Fenner, 1948, p. 883), those columnar-jointed, largely crystalline, but very porous tuffs, which are believed to be indurated by crystallization rather than by welding (Fenner, 1948, p. 883; Jenks and Goldich, 1956, p. 157), were probably incipiently welded before they crystallized. Specimens of salmon and white sillars kindly given to C. S. Ross and the writer by Fenner, are interpreted by the writer to be incipiently welded. Some of the specimens of salmon sillar show practically no crystallization but are firmly coherent. They show slight deformation of shards in thin sections and incipient compaction foliation in hand specimens. The white sillar, on the other hand, is completely crystalline and could represent salmon sillar that has crystallized in the vapor-phase zone of a cooling unit.

The sillar-type tuffs were probably emplaced at temperatures as high as that of many densely welded tuffs but the load pressure within the deposits was insufficient to cause obvious visible deformation of the glass before crystallization (white sillar) or cooling below the minimum welding temperature (salmon sillar) began. If these tuffs could be traced horizontally into thicker cooling units, the degree of welding would increase greatly.

The transition from incipient to complete welding is one of progressive loss of pore space accompanied by an increase in deformation of the shards and pumiceous fragments (pl. 21*A*–*F*). The progressive flattening of shards and pumice produces the streaky foliate structure long known as eutaxitic structure, which can be seen in outcrop, hand specimen, and under the microscope.

In most welded tuffs complete welding is probably achieved by simple load deformation, without stretching of particles, other than that necessary for local accommodation to available space. Crinkling or crenulation around crystal or rock fragments is common, and in many pumice-rich or inclusion-rich tuffs wavy eutaxitic foliation is normal.

Flattened pumiceous fragments, depending on their primary shape, are normally disclike in the plane of flattening. However, in some tuffs, usually in the lower part of the cooling unit, the fragments are elongate rather than disclike and show a preferred orientation. In most such examples probably some mass flowage has taken place in the sheet during welding. In welded tuffs of this kind observed by the writer, the stretching could have been accomplished by mass movement of from less than a few inches to a maximum of a few feet. Such mass flowage might be related to buried topography, earth movements during welding, or other factors, and more rarely, might be of greater magnitude.

CRYSTALLIZATION

Crystallization of the glass takes place in many ash flows subsequent to, or perhaps in part synchronous with, the welding process. Physically and (or) chemically different environments within the cooling unit may give rise to different types of crystallization. These may, depending on the degree of their development, be recognized as distinct, although overlapping, entities, and together with the degree of welding, can be potential guides to relative position within a deposit.

Three principal categories of crystallization which may take place during cooling are recognized by the writer. In order of frequency of occurrence, these are devitrification, vapor-phase crystallization, and granophyric crystallization. Throughout the report the term "cooling-history crystallization" refers to these three types, and to fumarolic alteration unless otherwise specified. The principal categories of cooling-history crystallization may be defined as follows:

Devitrification.—Crystallization of glass to form spherulitic and axiolitic intergrowths and aggregates, chiefly of cristobalite and feldspar. This crystallization is confined within glass fragments or massive glass. It is common to all crystallized silicic welded tuffs.

Vapor-phase crystallization.—The growth of crystals, from a vapor phase, in pore spaces. Vapor-phase crystallization is, in general, a coarser grained crystallization than devitrification, and is commonly manifest in the porous upper parts of welded ash flows where it is contemporary with, or follows, devitrification. In rhyolitic ash flows the predominant vapor-phase minerals are alkalic feldspar, tridymite, and cristobalite.

Granophyric crystallization.—In silicic welded tuffs granophyric crystallization is characterized by groundmass quartz intergrown with, or as blebs associated with, alkalic feldspar and minor accessory minerals. The aggregate shows granophyric or micrographic textures similar to those shown by many slowly cooled rhyolitic flows, domes, and shallow intrusive rocks.

Granophyric crystallization (quartz) has never been seen by the writer in fresh unaltered welded tuffs that were less than about 600 feet thick. However, many older deposits and ultimately all deposits will probably contain quartz as the groundmass silica mineral, through conversion of critobalite and tridymite.

A fourth category of cooling-history crystallization or, probably more precisely, alteration, should be rec-

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EXPLANATION OF PLATE 21

ZONES OF NO WELDING, PARTIAL WELDING, AND DENSE WELDING, AND THEIR APPROXIMATE CRYSTALLINE EQUIVALENTS

Specimens *A–F* show transition from zone of no welding to zone of dense welding. Specimens *G–L* show approximate crystalline equivalents in zones of partial welding and dense welding. *A–E*, from Battleship Rock, Jemez Springs quadrangle; *G–I*, from the Bandelier rhyolite tuff (Smith, 1938), Jemez Mountains, N. Mex.

A. Zone of no welding. Pumice blocks and lapilli in an unconsolidated ashy matrix. Some accidental rock fragments.

B. Zone of partial welding (upper part of upper zone). Shows incipient compaction foliation. Fracture takes place through, rather than around pumice fragments. Matrix ash more gray than in *A*.

C. Zone of partial welding (upper zone). Compaction foliation well developed, pumice fragments darker with less pore space and more vitreous luster than in *B*. By contrast, the ashy matrix still has a dull luster and hackly fracture.

D. Zone of partial welding (lower part of upper zone). Collapsed pumice lenticles and matrix ash have vitreous luster and conchoidal fracture although pore space is still about 20 percent.

E. Zone of partial welding (near transition to zone of dense welding). Collapsed pumice lenticles obsidianlike without pores although traces of former vesicles can still be seen in thin section.

F. Zone of dense welding. Dense black obsidianlike glass of virtually zero porosity. Collapsed pumice fragments only faintly visible in hand specimen. Their boundaries are visible in thin section but former vesicular structures have been partly to completely homogenized by welding. From km 153, Taxco Highway, Central Mexico. Collected by Carl Fries, Jr.

G. Vapor-phase zone (upper part of upper zone of partial welding). Slight compaction foliation; completely devitrified. Pumice fragments crystallized into drusy growths of tridymite and alkalic feldspar and some cristobalite. The pumice-tube structure is well preserved. Approximate crystalline equivalent to *B*. Very similar, except for fragment size, to white sillar described by Fenner.

H. Vapor-phase zone (upper zone of partial welding). Compaction foliation well developed. Pumice-tube structure not as well preserved in this plane, but very obvious in the plane of flattening. Approximate crystalline equivalent to *C*.

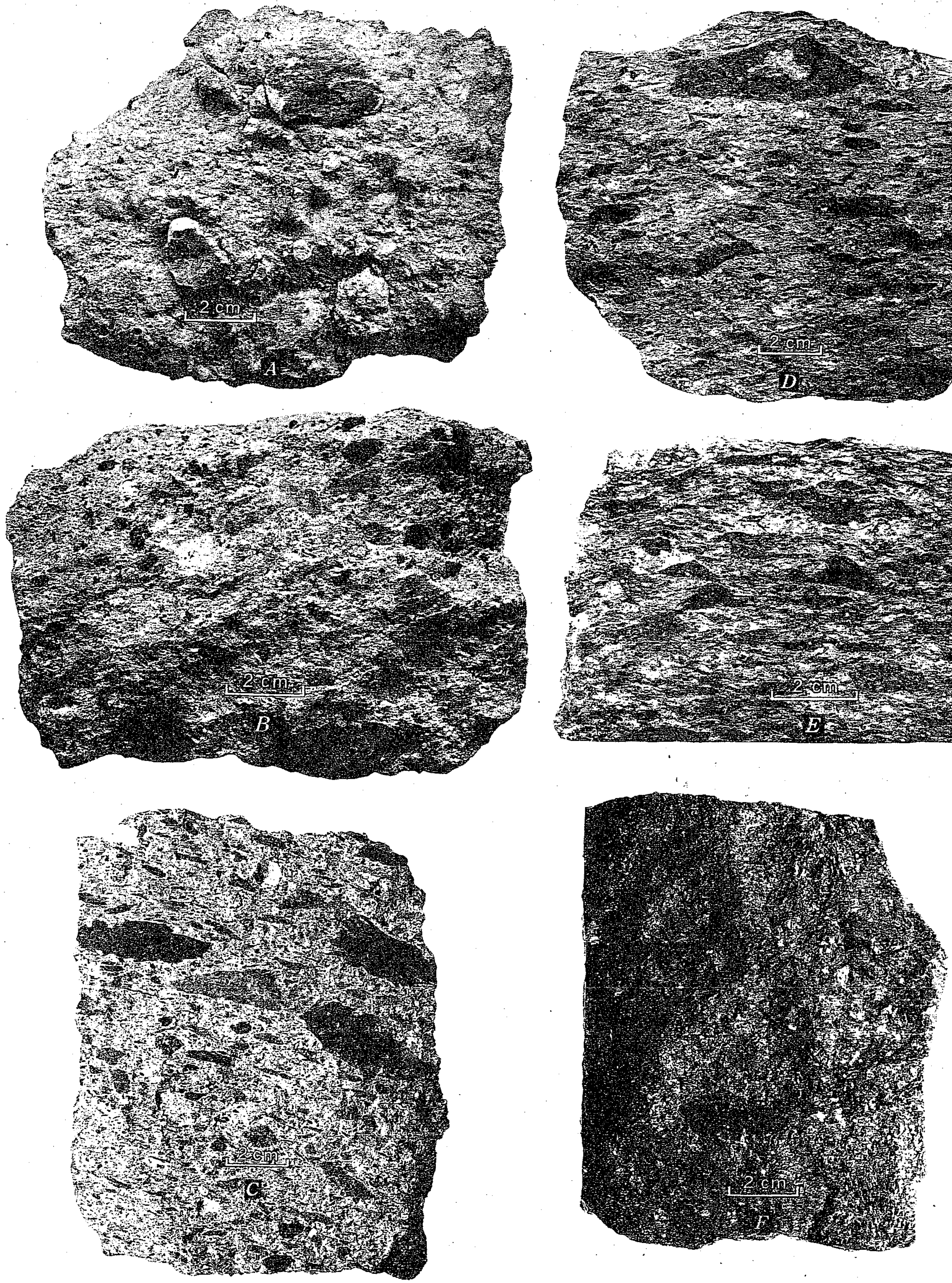
I. Devitrified zone (zone of dense welding). Some collapsed pumice fragments visible. In thin section this specimen shows coarse axiolitic devitrification.

J. Devitrified zone near base (zone of dense welding). Fine-grained devitrification of a dense black glass. Only faint traces of original pyroclastic character preserved in hand specimen. Perfect preservation of shards and flattened pumice fragments in thin section. Crystalline equivalent to *F*. Matahina ash flow, Rangitaiki Gorge, North Island, New Zealand. Collected by R. A. Bailey.

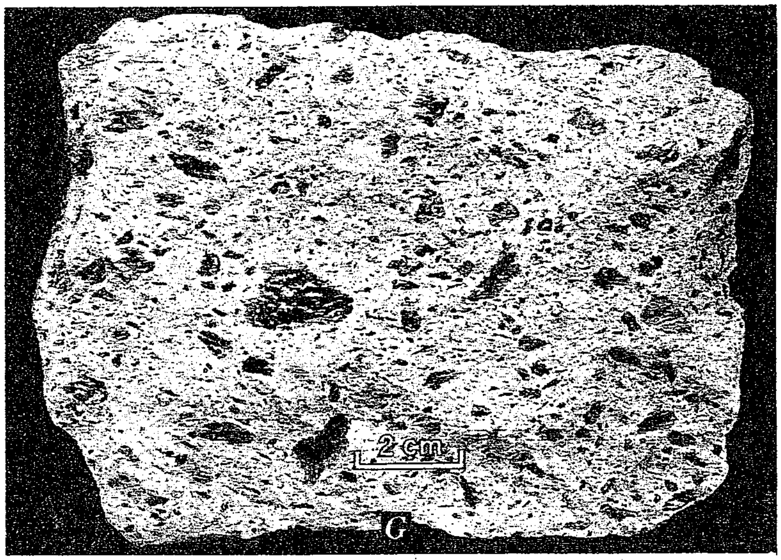
K. Specimen showing the effect of gas trapped during welding. The rock belongs in the zone of dense welding but the collapsed pumice fragments are miarolitic and coarsely crystalline. From the lower part of Enlows' (1955) member 6, Rhyolite Canyon formation, Bonita Canyon, Chiricahua National Monument, Ariz.

L. Lithophysal cavities in the devitrified zone of dense welding. This rock is composed of fine-grained pyroclastic materials which probably caused lithophysae to form instead of miarolitic cavities in pumice fragments. From the Ammon quadrangle, Idaho.

PLATE 21



PROFESSIONAL PAPER 354 PLATE 21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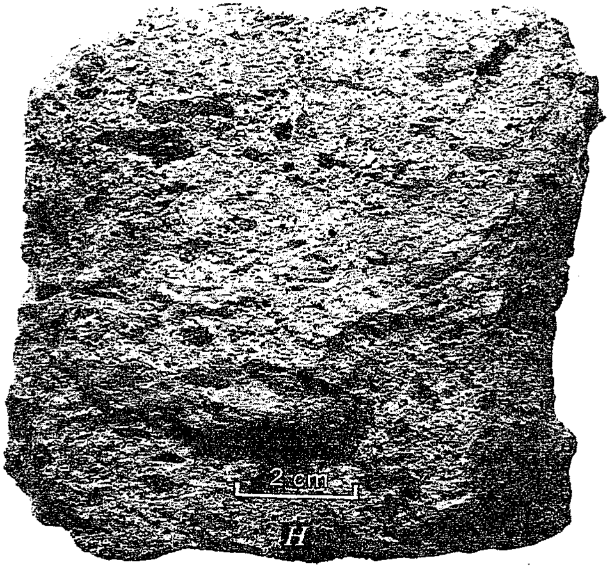
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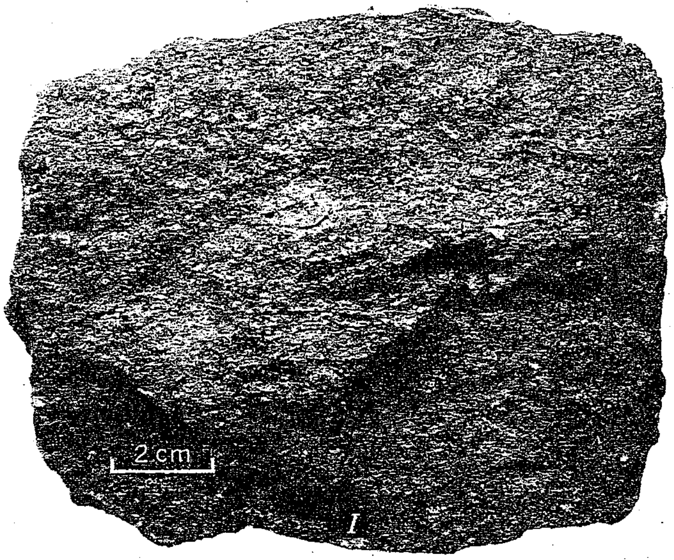
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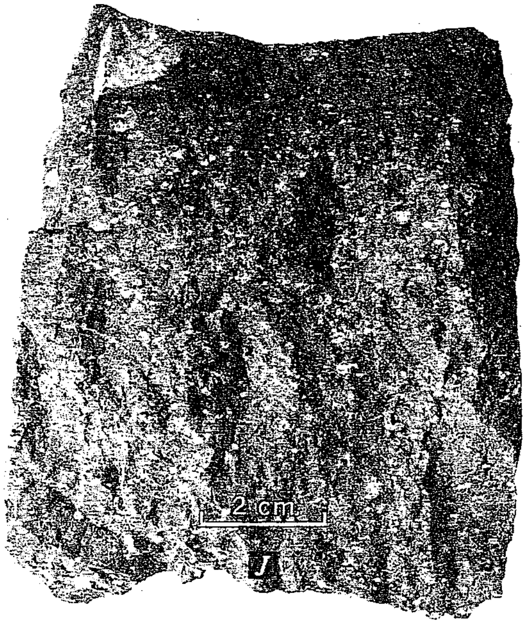
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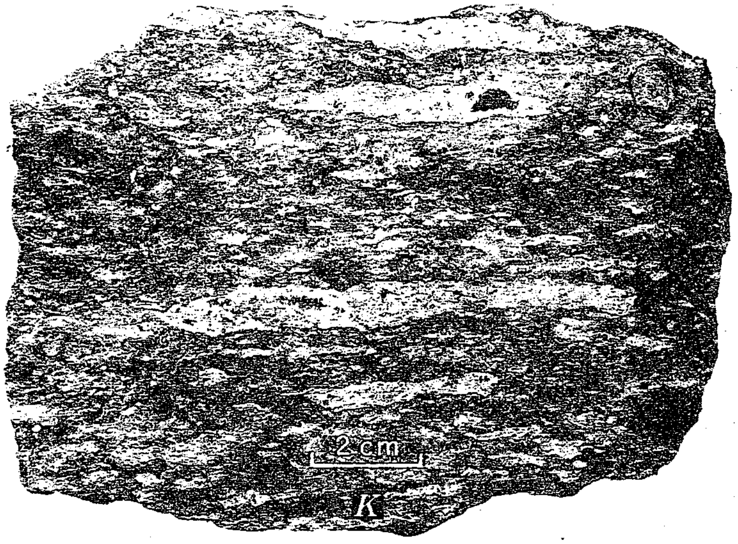
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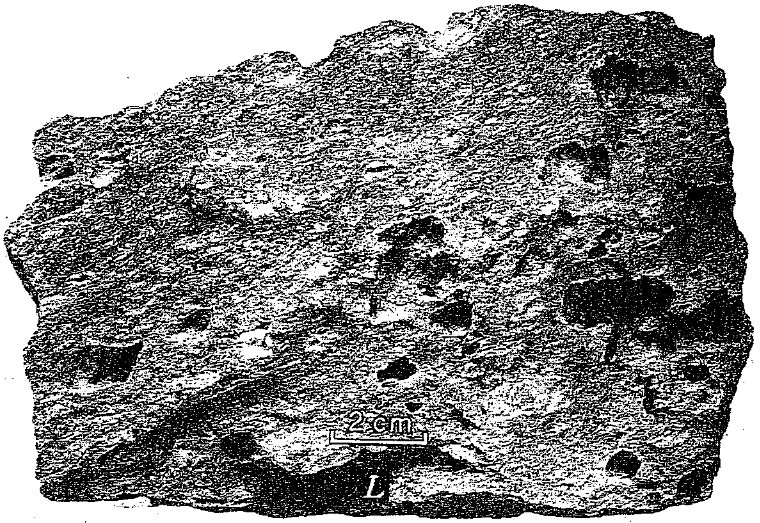
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ognizable in many deposits. This little-studied and generally unrecognized (in older deposits) process is fumarolic alteration. Some geologists may argue that this process is not basically different from vapor-phase crystallization, but the products are notably different and, generally belong to lower temperature and pressure environments.

Devitrification of the glass after initial cooling, and other forms of low-grade alteration need much discussion, but these should be considered in well-documented papers. Correct interpretation of cooling-history processes is obstructed by post-cooling-history, hydration, devitrification or other alteration of glass, oxidation of iron, and conversion of tridymite and cristobalite to opal, chalcedony, or quartz, and related processes. Some of these processes take place during as well as after cooling, and the knowledge necessary to always distinguish between the two has not yet been acquired. In Pleistocene and Recent rocks the problems are minor or nonexistent, but in some Pliocene and in most Miocene and older formations many physical and chemical properties of the rocks seem to have been affected by processes that occurred after cooling. Depth of burial and ground-water conditions are extremely important factors. Many geologists consider these altered rocks to be fresh and unaltered.

These alteration effects are often of regional extent and can best be interpreted as low-grade metamorphic reactions.

THE ZONES

All ash flows in which welding or crystallization have taken place show zonal variations in texture, color, or other features. These variations are dependent upon such factors as temperature, thickness of the deposit, composition of the ash, amount and composition of volatile constituents, and the ratio of pumice fragments to shards.

Any system that includes several variables where one variable can change the entire appearance of a rock body, or any part of it, is a very flexible system, and must be treated as such. The chance that two or more welded ash flows will show no differences as a whole is extremely slight. On the other hand, the close similarities that commonly exist between some welded ash flows may be confusing and it may be impossible to distinguish between their equivalent zonal facies. Differentiation may then be dependent upon detailed petrographic studies of phenocrystic minerals coupled with careful field study.

The zones shown in plate 20 are those which can be easily recognized or inferred in the field. Recognition of minor zones depends on the microscopic study; they are briefly mentioned in the following discussions of the individual major zones. All zone boundaries are transitional, some more abruptly than others. In general the boundaries of the basal zones are more sharply defined than those of the upper zones.

The ordered sequence of overlapping zones is best visualized by examining first the zones formed during the welding process without crystallization upon cooling. If welding proceeds to completion in any part of an ash flow, three distinct zones will be formed. These are the *zone of no welding*, the *zone of partial welding*, and the *zone of dense welding* (pl. 20 *A*,*B*). The *upper* zones of no welding and partial welding will be separated from the *lower* zones of no welding and partial welding by the zone of dense welding. Where sufficient lateral thinning of the ash flow occurs, such as the normal distal ends and margins, points will be reached where the upper and lower zones of partial welding will merge and grade into the nonwelded mantle of the deposit.

This simple pattern of zones is illustrated in plate 20*A* and *B*. Plate 20*B* shows the zonal relations in an extremely hot and moderately thin ash flow whereas plate 20*A* shows the zonal relations in a thicker ash flow emplaced at much lower temperature. Plate 20*B* also shows an additional zone which represents an early stage of crystallization. This additional zone in no way affects the comparison of the other zones illustrated in plate 20*A* and *B*. An ash flow emplaced at a temperature too low for welding is not shown, but is represented by the nonwelded mantle (pl. 20*A*). All transitions between this low-temperature extreme and the hot, densely welded type shown in plate 20*B* can occur. However, as temperature and thickness are increased together, a point will be reached where crystallization begins; thus the type of tuff illustrated in plate 20*B* can never reach great thickness and remain glassy throughout during cooling.

The glass of densely welded tuff that is of the order of thickness shown in plate 20*A* and *B* will probably be charged with spherulites or lithophysae or both, although these may vary in number and character with the initial gas content.

Crystallization usually follows, but may in part, accompany the welding process. This crystallization may occur in a narrow zone confined to the deep interior of the cooling unit or as a broad zone which may overlap, horizontally at least, all other zones formed during welding. All transitions between the two extremes may occur.

The character of crystallization is strongly influenced by the degree of welding of that part of the tuff upon which it is superimposed, the rate of cooling of the ash flow, and the amount and composition of volatile materials that it contains. Differences in character of crystallization, then, add another set of zones controlled in part by the zones already formed during welding, and in part by other factors.

ZONE OF NO WELDING

The *zone of no welding* is that part of an ash flow in which no welding has taken place (pl. 21*A*). This zone may comprise the entire ash flow or only a small part. Most single ash-flow cooling units have a nonwelded top and bottom (pl. 20*A*), although in some of the very hot flows the nonwelded bottom may not be present under the entire sheet (pl. 20*B* and *C*). In these very hot ash flows densely or partly welded tuff may extend to the base of the unit, especially near the source area.

The nonwelded zone will probably contain some incipiently welded tuff, especially in the crystalline units, because as mentioned on page 151, the only practical way to locate the zone boundary is by megascopic detection of deformation or compaction foliation. Incipient welding occurs at some point before this.

The nonwelded zone is commonly the least spectacular part of a welded ash flow, but is probably the most important zone because it is the only one that shows the original character of the erupted materials. Its preservation is necessary to such measurements as initial density and porosity, size analyses, and to the nature of the primary glass. For the most accurate characterization of the magma, chemical analyses should be made of pumice from this zone (pl. 21*A*), providing that the rocks are fresh and the pumice is not foreign material. Most middle to early Tertiary and apparently all known pre-Cretaceous ash-flow tuffs show some alteration in this zone beyond simple hydration of the glass and are not too helpful in understanding the chemistry of the primary magma.

ZONE OF PARTIAL WELDING

The *zone of partial welding* includes all material ranging from that which shows incipient welding to that which has lost virtually all its pore space (pl. 21*B–E*). This zone shows a greater diversity of textures than any of the other zones because of the wide range in porosity and degree of deformation of its glassy parts. The boundary between the zones of partial and dense welding is discussed below.

Further subdivision of the zone might have practical application in some welded ash flows. For example, a measure of the degree of collapse of pumice fragments can be an important factor in determining the relative vertical position of material in the sheet.

In some cooling units the upper zone of partial welding may extend horizontally for many miles without much apparent change in thickness as long as it is underlain by a zone of dense welding.

The zone of partial welding is best developed in colder ash flows (pl. 20*A*) and is poorly developed in very hot ash flows (pl. 20*B*). The thickness of this zone is therefore, in a general way, an index of the emplacement temperature of the ash flows.

ZONE OF DENSE WELDING

Ideally the *zone of dense welding* should be defined as that zone in which complete coalescence of the glassy fragments has resulted in the elimination of all pore space. A dense black glass or vitrophyre is the normal product of this process (pl. 21*F*). Actually it will be a rare welded tuff that is completely pore free, exclusive of the *vitrophyre zone* in some sheets, because of processes other than welding that help determine the final character of the rock. Entrapped or exsolved gas, for example, causing the formation of lithophysal (pl. 21*L*) or other types of cavities, may inhibit complete loss of pore space in this zone during welding. However, in the groundmass surrounding these porous areas, complete welding of the shards will show that the rock is in the zone of dense welding. The boundary between the zone of dense welding and the upper zone of partial welding marks a plane below which the rock is pore free, or potentially pore free were it not for entrapped gas, and above which the rock would be porous, with or without gas entrapment. Crystallization of a pore-free glass may result in a slightly porous rock. All these factors must be considered in distinguishing the zone of dense welding from the zone of partial welding.

If the welded tuff remains glassy upon cooling, all the zones and zonal transitions are generally well defined and simple, although in the simple cooling units the transitions above the zone of dense welding are less sharply defined than those below. However, when crystallization takes place, the upper transitions may become obscure, and the exact location of the zone boundaries in some sheets will be largely subjective, particularly in crystal-rich quartz latites and rhyodacites.

The transition from partial to dense welding in glassy welded tuffs is best shown by changes in the pumice fragments present in most ash flows. In fresh rocks and those that have had a simple cooling history, the pumiceous fragments and blocks change by decreasing porosity and a general darkening of color until they become black and obsidianlike (pl. 21*A–F*).

The darkening of the pumiceous fragments precedes the darkening of the shardy matrix. For field purposes the end stage of the welding process is a dense black glass in which the pumiceous fragments and the matrix are megascopically indistinguishable.

Complete welding is not achieved until the pumiceous fragments, shards, and glass dust are homogenized; all grain boundaries disappear and, exclusive of crystals and inclusions, a completely homogenous glass is formed. This *zone of homogenization* can only be proven by microscopic study in conjunction with field study, and will be found only rarely, probably for the following reasons: (a) In ash flows initially thin enough or cold enough to remain uncrystallized after cooling, temperatures and pressures high enough to cause homogenization of the glass particles are rare; (b) in thick cooling units where a zone of complete homogenization might occur, this zone will likely crystallize on cooling and may be indistinguishable from nonhomogenized welded tuff whose vitroclastic structure has been obliterated by crystallization. Partial homogenization of tube structures in pumice fragments is common in some glassy welded tuffs but complete homogenization is rare. Tube structures refer to tubular vesicles which are more common than spherical vesicles in pumice from tuffs of silicic composition. These tubes are sometimes so fine that they present a fibrous appearance and cause the pumice to have a silky luster. The writer has never seen complete obliteration of shard boundaries in glassy rocks but it will no doubt be found, and it is for this reason that the point of homogenization is emphasized.

The vitrophyre zone generally shows a transition downward through a partly welded zone to a nonwelded base which may range from almost zero to many feet in thickness. However, some flows were emplaced at such high temperature that the vitrophyre zone extends to the base of the cooling unit and, in some vertical sections, may extend below the base of the unit as a fused zone in underlying glassy pyroclastic deposits (pl. 20*D*). This fused selvage will probably never be more than a few feet thick. If the underlying material is bedded ash, the bedding may still be preserved in the vitrophyre. An excellent example of this basal fusion has been described by Boyd.[1]

The vitrophyre zone (pl. 20*C* and *D*) is often the most useful part of a cooling unit for mapping purposes, especially in complexly faulted rocks, as it provides a useful marker unit.

ZONES OF CRYSTALLIZATION

A large proportion of welded ash flows have crystallized to some degree upon cooling. Crystallization may be incipient or intensely pervasive. Incipient crystallization may be marked by growths of minute spherulites in the zone of dense welding, or by the presence of vapor-phase or fumarolic minerals in scattered fine-grained growths in the upper porous zones. Crystallization may also be so extensive throughout the cooling unit that only a very thin chilled base, top, and distal end of the unit will remain glassy after cooling. Crystallization in most welded ash flows will fall somewhere between the two extremes (pl. 20*C*).

Devitrification is the most common crystallization process and in most cooling units the products of devitrification will be present throughout the entire crystalline zone. However, in some porous rocks these products will be subordinate to those of vapor-phase crystallization because of intense vapor-phase activity.

In rhyolitic tuffs, devitrification consists of the simultaneous crystallization of cristobalite and alkalic feldspar to form submicroscopic spherulitic and axiolitic intergrowths of these minerals plus minor accessory minerals. This devitrification process is confined within shards or glass masses, whereas crystallization by growth of crystals into pore spaces is a different process related to the movement of vapors and transfer of material. Without pore space, vapor-phase crystallization cannot take place. Thus in densely welded tuff that has not entrapped large quantities of gas, devitrification is the dominant and commonly the only process of crystallization. For this reason the writer refers to the crystallized part of the zone of dense welding as the *devitrified zone* (pl. 21*I* and *J*). The crystalline porous zone is referred to as the *vapor-phase zone* (pl. 21*G* and *H*), if it contains crystal growths in the pore spaces, or if it is probable that it had crystal growths in the pore spaces.

The ideal boundary between that part of the zone of devitrification that contains the vapor-phase zone, and that part in which the vapor phase does not occur is the boundary between the zone of dense welding and the upper zone of partial welding (pl. 20*C*). The abrupt appearance of the lower boundary of the vapor-phase zone will depend on the sharpness of transition between the glassy zones before crystallization. In some tuffs this transition may take place within a few feet, whereas in others it may be so broad that it may be difficult to detect at all.

Some of the features that may mark this transition are: (a) The upward appearance of vapor-phase minerals; (b) a visible upward increase in porosity; (c)

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[1] Boyd, F. R., 1957, Geology of the Yellowstone rhyolite plateau: Ph. D. thesis, Harvard Univ., 134 p.

a downward change in color or shading of color from light to dark; (d) a downward change from coarse to fine joint spacing; and (e) the zone of dense welding is usually a better cliff former in crystalline tuffs.

Curves derived from density or porosity measurements of vertical sections of simple cooling units may sometimes show that a porosity gradient exists in the zone of dense welding. Ideally the porosity of a vertical section of a cooling unit should show no change in the zone of dense welding. However, the ideal is not usually achieved except in the vitrophyre zone or in the basal part of some devitrified zones. Thus in some cooling units, there is a slight, perhaps irregular, but steady increase in porosity upward from a point near the base of the devitrified zone to the top of the zone of dense welding. Above this point the porosity increases more rapidly and the transition is marked on porosity curves by a change in slope of the curve. The writer suggests that where this porosity gradient does exist in the zone of dense welding, it reflects a lithostatic pressure gradient, but exists owing to the direct or indirect effects of entrapped gas that acted as a deterrent to uniform completion of the welding process.

Thick hot gas-rich ash flows may weld so fast that gas is entrapped throughout all but a relatively thin basal zone. Pumice fragments commonly serve as loci for the entrapped gas, and crystallization of these gives rise to streaky eutaxitic folia, some of which are cavernous and more coarsely crystalline than the densely welded groundmass shards surrounding them (pl. 21*K*). Unless these tuffs are very young and fresh, it may be difficult or impossible to differentiate between the vapor-phase crystallization around the entrapped-gas cavities and the true continuous vapor-phase zone above the zone of dense welding. Thus in some ash-flow cooling units recognition of the vapor-phase zone may be of questionable importance. However, in others differentiation of the vapor-phaze zone, from vapor-phase crystallization in lenticular or lithophysal cavities in the zone of dense welding, may be highly important for the following reasons: (a) Stratigraphic significance; (b) petrologic and mineralogic interest; (c) because this zone is one of active rising vapors and it is here that changes may take place in chemical composition due to vapor-phase transfer of materials. Preliminary investigations indicate that appreciable chemical differences (in both major and minor elements) may be found between this and other zones.

Mafic phenocrysts, especially biotite, hornblende, and orthopyroxene, are commonly in part or wholly destroyed by the crystallization processes. Their former presence may be confirmed by the distribution of opaque oxides, relicts, and their existence in the vitric zones. In extreme examples a new generation of mafic minerals may be formed (biotite, amphibole, fayalite, and others).

In fresh rhyolitic rocks the appearance of tridymite with drusy feldspar usually indicates the presence of a vapor-phase zone (pl. 21*G* and *H*). Commonly these crystal druses are localized in pumice fragments and show varying degrees of lenticularity depending on the amount of flattening of the pumice fragment during welding. The former pumice-tube structures are often preserved in these crystal aggregates and can be seen in the field by the unaided eye. In older or less fresh rocks (middle Tertiary and older) these vapor-phase crystals have commonly been replaced by opal, chalcedony, quartz or other minerals and their original structure may no longer be recognizable.

The writer believes that most of the groundmass quartz that is seen in some welded tuffs is probably secondary, having formed through the conversion of cristobalite or tridymite by diagenetic or low-grade metamorphic processes. However, sometimes quartz is seen deep in the interior of the devitrified zone of very thick ash-flow cooling units, where it is probably primary in the sense that it formed during the cooling history of the cooling unit. The textures formed are similar to those seen in granophyric rocks. Conditions might exist within very hot thick ash flows where quartz would form in preference to cristobalite as the groundmass silica mineral, or early formed cristobalite might be converted to quartz during later stages of cooling. This would give rise to a *zone of granophyric crystallization* separating the devitrified zone into upper and lower parts.

Poor preservation or complete obliteration of vitroclastic textures might be expected in very thick cooling units. Several variables are involved hence the minimum thickness of tuff necessary for the formation of this zone is problematical. The writer has never seen what he would interpret to be primary groundmass quartz in any welded tuff unit less than about 600 feet thick.

Speculation on the probable nature of a very hot gas-rich cooling unit that is 2,000 feet or more thick seems warranted. No doubt thicknesses of this magnitude will be found. Welding would be almost instantaneous throughout most of the sheet and much gas would be entrapped. Slow cooling could be expected and a long stage of deuteric activity would produce a granophyric groundmass in which former pyroclastic textures could be completely destroyed.

Without excellent exposures to reveal the contact relations, such a rock body could easily be interpreted as an intrusive mass. Even the contacts might be expected to show injection phenomena. Some ash flows are hot enough to cause fusion of underlying glassy ash or to weld almost completely against low porosity rocks that are relatively fast heat conductors. Such welded material under high load could inject cracks and crevices. Crystallization might also extend to the base of such a rock body. The zone of granophyric crystallization might then occupy a large proportion of the cooling unit.

Any ash flow that contains hot gas or is emplaced at a temperature high enough to crystallize on cooling should give off gas at its surface. The amount, composition, and temperature of this gas, along with other factors, will determine the degree of alteration of the surface and upper parts of the deposit including joint cracks. By this reasoning, and by analogy with historic ash-flow deposits such as the Valley of Ten Thousand Smokes (Zies, 1929, p. 1–79) and the Komagatake deposits (Kozu, 1934, p. 164–174), many ash flows should show a *zone of fumarolic alteration* transitional with the vapor-phase zone and with, perhaps, more intense alteration localized by deep joints. Surface sublimates and some near-surface alteration products are probably rapidly reworked by water entering the deposits. Some are no doubt removed entirely, but others are probably lodged in the soft tops of the cooling units.

Where these ash-flow tops are preserved in rocks of silicic composition, pale but decidedly variegated color patterns may indicate the presence of former fumarolic activity. These color patterns are in contrast to the uniform chalky white, gray, pink, lavendar, red, brown, or purplish groundmass colors of the vapor-phase zone. Mild fumarolic alteration has been recognized in prehistoric deposits by Gilbert (1938, p. 1851–1854), Williams (1942, p. 86–87), and Mackin (1952, p. 1337–1338).

COOLING UNIT

Unimpeded cooling of ash flows emplaced above the minimum welding temperature results in a deposit that shows a pattern of zones resembling closely (a) plate 20*A*, *B*, or *C*; (b) some intermediate stage between the diagrams; or (c) a vertical segment of these diagrams or intermediate stages. Such deposits may be called *simple cooling units*. Multiple flow units may also form a simple cooling unit provided they are emplaced in such rapid succession that there is no hiatus in cooling which cannot be bridged by successive flows (pl. 20*D*).

In a given vertical section of a simple cooling unit it may be impossible to distinguish between flow units, and the recognition of partings between them may only be possible because of horizontal changes in the sheet. Partings that exist in the nonwelded and partly welded zones will probably be easily seen. However, those occurring in the densely welded zone, especially after crystallization, may be invisible for many miles, depending on the characteristics of the partings.

Partings between successive ash flows within a single cooling unit may be marked by the following: (a) Concentrations of lump pumice; (b) fine- to coarse-bedded air-fall ash, lapilli, or blocks; (c) bedded ash from a reworking of the surface of the ash flow by wind or water; and (d) minor erosional unconformities. In the absence of these criteria, the ash flows may in places be distinguished on the basis of abrupt changes in their physical or chemical makeup. Such properties as grain size, phenocryst ratios, chemical or mineralogical composition, color and inclusions should be considered. In some densely welded tuffs where partings between ash flows are obscure, preferential weathering or slight irregularities in density or porosity may suggest their presence. Any, all, or none of these highly variable factors may be significant in a simple cooling unit.

Pronounced deviations in the pattern of zones as outlined for simple cooling units seem to indicate breaks in the cooling history of given cooling units and suggest compound cooling. These *compound cooling units* can show infinite variation between simple cooling units and separate cooling units. In other words, a simple cooling unit may, by horizontal gradation, become a compound cooling unit which, in turn, may grade into two or more simple or compound cooling units.

A few of the more obvious features that suggest compound cooling are: (a) Reversal of relative thickness of upper and lower zone of partial welding; (b) extensive development of vapor-phase zone below a devitrified zone of dense welding with a transitional contact between the two zones; (c) basal nonwelded zone which is many times thicker than overlying zones; (d) visible reversals in density or porosity within the zones of welding exclusive of those related to differing mineral facies; (e) extensive development of columnar joints below a zone of dense welding.

Some of the factors contributing to compound cooling are: (a) Unequal areal distribution of individual ash flows; (b) degree of development of some of the phenomena which cause the partings listed above; (c) successive emplacement of ash flows of radically different temperatures; and (d) periodicity of eruptions.

The cooling unit, either simple or compound, is probably the logical map unit in most unmetamorphosed rocks. It is a closely limited time unit as well as a genetic rock unit. Distinguishing between individual flow units is generally not practical and is impossible in many situations. In many areas, mapping of at least the more spectacular zones of the cooling unit is practical, and in detailed studies, recognition and mapping of the zones as integral parts of a unit may help solve many problems of structure and stratigraphy.

COMPOSITE SHEET

A hypothetical unit, the *composite sheet*, is discussed because its existence seems inevitable now that many of the diverse characteristics of the cooling units are known. The writer has examined ash-flow deposits which can be explained only on the assumption that they are part of a unit of higher rank than the cooling units. The evidence consists of observed horizontal change of compound cooling units into separate cooling units. That is, the composite sheet is composed of cooling units that may range horizontally through any or every stage from a single- or multiple-flow simple cooling unit, multiple-flow compound cooling unit, to cooling units that are separated by erosional unconformities, other volcanic or sedimentary deposits, or local hiatuses in time sufficient to allow cooling of one unit before another is emplaced on top of it. Detailed mapping for documentation of this concept is necessary.

At any given time during its emplacement cycle the composite sheet is visualized as undergoing continuous cooling throughout some of its few tens to few thousands of square miles of area. The merging or overlap of composite sheets or cooling units from different source areas would give rise to many complexities. The time-stratigraphic importance of such a relation might be very great, especially if air-fall deposits can be related to the ash-flow sheets.

INFLUENCE OF BURIED TOPOGRAPHY

The zonal variations expected to occur where a simple cooling unit is superimposed on a high or low feature in the underlying topography are shown in plate 20*D*. The effects are the same as would be expected from normal horizontal thinning or thickening, but the changes are more abrupt.

The changes due to buried topography may be striking in regions of high relief, but in regions of low relief they are more subtle. For example, the distribution of outcrops of a persistent dense glass zone may suddenly become erratic. One explanation might be that the cooling unit was emplaced on an irregular surface such that the tops of the buried topographic high areas were roughly coincident with the level in the cooling unit that marks the transition from the zone of dense welding to the upper zone of partial welding. A dense black glass could not form over any topographic high that reached this transition level. In sheets of this type, buried topography will also be reflected by gentle irregularities in the surface of the cooling unit.

Other variables being equal, the thickness of the cooling unit (producing load pressure) at any point controls the amount and degree of welding at that point. Thus the percent of total compaction will be greater in the thicker parts of the unit, and it is this differential compaction that results in surface expression of buried topography. If two cooling units of equal emplacement thickness are of different compactability, the one with the higher compactability will show the more irregular surface over equivalent buried topography.

By careful consideration of plate 20*D*, the effect of buried topography can be predicted for other zones and different topographic environments. The extreme abruptness of changes in the cooling-unit surface and the zones as shown in plate 20*D* is due to the vertical exaggeration of the projection.

Some cooling units (map units) can change abruptly over a buried escarpment, resulting in thick welded tuff on one side and a thinner nonwelded or only partly welded tuff on the other. As shown in plate 20*D*, the thick side of the buried escarpment contains a vitrophyre zone and a devitrified zone of dense welding, whereas the other side is predominantly a "sillar" type of tuff (p. 151). If such a situation as this were to be found in deformed and eroded terrane, with poor exposures, the chances of correct interpretation would probably be small even for experienced geologists. It would present difficulties even under ideal field conditions. Infinite variation is possible, especially if compound cooling or composite sheet effects are involved.

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