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ASH FLOWS

By Robert L. Smith

Abstract

The ash flow is the basic unit of most pyroclastic deposits known as welded tuffs, tuff flows, pumice flows, or ignimbrites. Other useful units are the cooling unit, both simple and compound, the composite sheet, and the ash-flow field. The deposit of one ash flow is considered analogous to, but not necessarily the same as, the deposit produced by the passage of one nuée ardente. The geological evidence favors gas-emitting particulate flows as the agents of transport.

The ash-flow is an efficient heat-conserving mechanism, and, because many ash-flow fields contain cooling units believed to be derived from common magma, but clearly emplaced at different temperatures, a cooling mechanism must be invoked. Such a mechanism may be the vertical eruption column which influences the final properties of many ash flows.

Deposits are grouped in seven orders of magnitude ranging from 0.001 to 10,000 km³. Orders 1 to 3 include deposits erupted from domes. Those from craters rarely exceed 10 km³, order 4. Deposits of orders 5 to 7 are associated with subsidence structures in all examples where the source area is known. Welded tuffs occur in fields of all volumes, but they are common among the fissure-erupted deposits of larger volume. Some ash-flow fields distributed from a common source area reach areal dimensions of more than 12,000 square miles and volumes of about 500 cubic miles; some multiple-source fields are known to have volumes of more than 2000 cubic miles. Deposits of single-eruption cycles having volumes of more than a few cubic miles are thought to be related to subsidence structures.

Sorting data suggest that most welded tuffs contain more than 70 per cent by weight of materials less than 4 mm in diameter. Welding and crystallization depend largely on relative temperature and thickness of the cooling units, and most of the textures in welded ash flows can be explained in terms of these variables. Welding begins with incipient cohesion of glass shards and fragments and continues with decreasing pore space and deformation to complete welding which results in a dense black glass.

Crystallization is superimposed on the welded material at any stage, but the degree of welding may influence the type of crystallization. The degrees of welding and of crystallization are zonal and permit the distinction between simple and compound cooling. Incipient welding may take place below 535° C., but complete welding depends on load pressure and time and is thus influenced by the cooling history of individual cooling units. Deposits emplaced at low temperatures such as the Crater Lake, Oregon, "pumice flows" are essentially nonwelded in thick deposits. The high-temperature welded tuffs of southeastern Idaho are densely welded in very thin sheets. Most welded tuffs are probably emplaced at temperatures intermediate between these limits. Some deposits record a systematic change in temperature during the eruption cycle; others record a change in magmatic composition. Some ash flows are thought to be genetically related to near-surface plutons, some of which are large and complex.

Résumé

La coulée de cendres est l'élément de base de la plupart des dépôts pyroclastiques appelés tufs soudés, coulées de tufs, coulées de ponce, ou ignimbrites. D'autres éléments utiles sont le bloc de refroidissement, simple ou composé, la nappe composée, et le champ de cendres de coulées. Les dépôts d'une coulée de cendres sont considérés comme analogues, mais pas nécessairement identiques aux dépôts produits par le passage d'une seule nuée ardente. Les données géologiques sont en faveur de coulées en menues particules, et émettant des gaz, comme agents de transport.

La coulée de cendres est un mécanisme effectif de conservation de la chaleur, et parce que beaucoup de champs de cendres contiennent des blocs en refroidissement dont on pense qu'ils dérivent d'un magma commun, mais apparemment mis en place à des températures différentes, un mécanisme de refroidissement doit entrer en jeu. Un mécanisme

de ce genre pourrait être la colonne d'éruption verticale qui influe sur les propriétés ultimes de nombreuses coulées de cendres.

Les dépôts sont groupés en 7 ordres de grandeur, de 0,001 à 10.000 km³. Les ordres de 1 à 3 comprennent les dépôts venus de dômes. Ceux originaires de cratères dépassent rarement 10 km³, ordre 4. Les dépôts des ordres 5 à 7 sont associés à des structures de subsidence dans tous les exemples dont le lieu d'origine est connu. Les tufs soudés forment des champs de tous volumes, mais ils sont communs dans les dépôts d'origine fissurale et de grand volume. Certains champs de cendres venus d'un lieu d'origine commun atteignent des surfaces de plus de 30.000 km² et des volumes de plus de 2.000 km³; des champs d'origine multiples atteignent des volumes de 8.000 km³. On pense que les dépôts de cycles à une seule éruption qui ont des volumes de plus de quelques km³ sont en relation avec des structures de subsidence.

Les données granulométrique suggèrent que la plupart des tufs soudés contiennent plus de 70% en poids de matériaux de moins de 4 mm de diamètre. L'agglomération et la crystallisation dépendent largement de la température relative et de l'épaisseur des unités en refroidissement, et la plupart des textures rencontrées dans les coulées de cendres agglomérées peuvent d'expliquer en considérant ces variables. L'agglomération commence avec la cohésion naissante d'éclats et de fragments de verre, et continue par la diminution du volume des pores, et déformation, jusqu'à soudure complète qui aboutit à un verre noir dense.

La crystallisation se surajoute à n'importe quel stade dans le matériel aggloméré, mais le degré de soudure peut influer sur le type de crystallisation. Les stades d'agglomération et de crystallisation sont en zones, et permettent de distinguer le refroidissement simple du composé. L'agglomération naissante peut avoir lieu en dessous de 535° C., mais la soudure complète dépend de la pression et de la durée, donc est influencée par l'histoire du refroidissement des blocs individuels en refroidissement.

Les matériaux mis en place à basses températures, tels que les "coulées de ponce" de Crater Lake dans l'Oregon sont en grande partie non soudés dans les dépôts épais. Les tufs soudés à haute température du sud-est de l'Idaho sont densément soudés en couches très minces. La plupart des tufs soudés sont probablement mis en place à des températures intermédiaires entre ces extrêmes. Certains dépôts montrent un changement systématique de température pendant le cycle de l'éruption, d'autres montrent un changement de composition magmatique. On pense que certaines coulées de cendres sont liées génétiquement à des plutons proches de la surface dont certains sont de grande taille et de nature complexe.

Zusammenfassung

Der Aschenstrom ist die Grundeinheit der meisten pyroklastischen Ablagerungen, die als zusammen geschweisste Tuffe ("Schmelztuff"), Tuffströme, Bimsteinströme oder Ignimbrite bekannt geworden sind. Andere anwendbare Einheiten sind die einfache und die zusammengesetzte Abkühlungseinheit, die komplexe tafelförmige Masse, und das Aschenstromfeld. Man nimmt an, dass die Ablagerung eines Aschenstroms im allgemeinen analog zu der ist, welche durch die Passage eines nuée ardente ("Glutwolke") entsteht, aber nicht unbedingt dieselbe sein muss. Die geologischen Gegebenheiten sprechen dafür, dass gasausströmende Partikel-Ströme als Transportkräfte dienen.

Der Aschenstrom ist ein wirkungsvoller, Wärme konservierender Mechanismus. Da viele Aschenstromfelder Abkühlungseinheiten enthalten die wahrscheinlich von gewöhnlichem Magma abstammen, jedoch eindeutig bei anderen Temperaturen eingebettet worden sind nimmt man an dass ein Abkühlungsmechanismus dabei zur Hilfe gekommen sein muss. Die vertikale Eruptionssäule könnte solch ein Mechanismus sein, welcher die endgültigen Eigenschaften vieler Aschenregen beeinflusst.

Die Ablagerungen werden in sieben Grössenordnungen eingeteilt, welche von 0,001 km³ bis 10.000 km³ rangieren. Die Grössenordnungen 1 bis 3 schliessen Ablagerungen ein, die von Domen eruptiert sind. Kraterablagerungen übersteigen selten die Grössenordnung 4 (10 km³). Ablagerungen der Grössenordnungen 5 bis 7 sind in allen Fällen, wo das Ursprungsgebiet bekannt ist, mit Bodensenkungsstrukturen verbunden. Zusammen geschweisste Tuffe kommen in Feldern aller Grössenordnungen vor. Sie sind jedoch unter den aus Spalten eruptierten Ablagerungen grösseren Umfangs häufiger. Einige Aschenstromfelder, die von einem gemeinsamen Ursprungsgebiet aus verbreitet wurden, erreichen Flächendimensionen von über 30.000 km² und Volumen von etwa 2.000 km³. Es ist bekannt, dass einige Felder mit mehreren Ursprungsgebieten Volumen von über 8.000 km³ haben. Es wird angenommen, dass Ablagerungen von Einzel-Eruptions-

cyclen, welche ein Volumen mehr als einigen km³ haben, zu Absenkungs-Strukturen in Beziehung stehen.

Korngrössen-Analysen lassen vermuten, dass mehr als 70% des Gewichtes der meisten zusammen geschweissten Tuffe aus Materialien bestehen, die weniger als 4 mm im Durchmesser sind. Das Schweissen und Auskristallisieren hängt weitgehend von der relativen Temperatur und der Dicke der abkühlenden Einheiten ab, und die meisten Texturen in den zusammen geschweissten Aschenströmen können mit Hilfe dieser Variablen erklärt werden. Der Schweissprozess beginnt mit geringer Kohäsion von Glasscherben und -bruchstücken und verläuft weiter über abnehmenden Porenraum und Deformationen bis zu einem völligen Verschweissen, das in einem undurchsichtigen, schwarzen Glas endet.

Kristallisation kann in dem geschweissten Material in jedem Stadium auftreten, aber der Grad des Zusammenschweissens kann die Art der Kristallisation beeinflussen. Die Stufen von Zusammenschweissung und Kristallisation sind zonal angeordnet und erlauben die Unterscheidung von einfacher und komplexer Abkühlung. Beginnende Zusammenschweissung kann unter 535° C. stattfinden, aber vollständige Zusammenschweissung hängt vom Gewichtsdruck und von der Zeitspanne ab und ist so durch den Abkühlungsverlauf der individuellen Abkühlungseinheiten beeinflusst.

Ablagerungen, welche bei niedrigen Temperaturen eingebettet wurden, wie die "Bimsteinströme" am Crater Lake, Oregon, sind in dicken Lagern ausgesprochen ungeschweisst. Die Tuffe vom südöstlichen Idaho, welche bei hohen Temperaturen zusammen geschweisst wurden, sind in undurchsichtigen und sehr dünnen Lagen zusammen geschweisst. Die meisten zusammen geschweissten Tuffe sind wahrscheinlich bei Temperaturen, die darwischen liegen, eingebettet worden. Einige Ablagerungen weisen einen systematischen Temperaturwechsel während des Eruptionsreihes auf, andere zeigen einen Wechsel in der magmatischen Zusammensetzung. Man nimmt an, dass einige Aschenströme genetisch mit nahe der Erdoberfläche liegenden Plutonen verwandt sind, von denen einige von grossem Ausmass und komplexer Natur sind.

ПОТОКИ ВУЛКАНИЧЕСКОГО ПЕПЛА

Роберт Л. Смит

Резюме

Поток вулканического пепла является основной составной частью большинства пирокластических отложений. Эти отложения представлены сваренными туфами, туфовыми потоками, потоками пемзы, или игнимбритами. Другими элементами пирокластических отложений являются простые покровы и сложные залежи, образовавшиеся в результате остывания, отложения раскаленных лавин пепла. Отложение потока пепла аналогично отложению образованному после прохождения раскаленного облака. Однако это не означает, что эти отложения тождественны. Геологические данные говорят о том, что потоки мелких частиц, выделяющие газ, играют значительную роль в перенесе вулканического материала.

Поток вулканического пепла хорошо сохраняет тепло. Процесс остывания играет большую роль в образовании отложений потоков, содержащих остывшие залежи. Эти залежи, очевидно, связаны с общим магматическим источником и образовались при разной температуре. Процесс остывания может начаться с образования вертикального столба изверженного материала, который влияет на конечные свойства потоков.

Отложения потоков подразделяются по размерам на семь групп и их объем колеблется от 0,001 до 10 000 кубических километров. Группы от 1 до 3 включают извержения вулканических куполов. Отложения 4-й группы представлены продуктами извержения кратеров и редко превышают объем 10 кубических километров. Отложения групп от 5 до 7-й ассоциируются со структурами оседания во всех случаях, когда известен источник изверженного материала. Сваренные туфы встречаются в отложениях всех объемов, но они обычны среди отложений трещинных извержений большого объема. Некоторые отложения потоков вулканического пепла, происходящие из одного источника, покрывают площадь более 30 000 квадратных километров и достигают объема около 2 000 кубических километров. Некоторые отложения, имеющие несколько источников, дос-

тигают объема более 8 000 кубических километров. Отложения одиночных циклов извержений, имеющие объем равный нескольким кубическим километрам, вероятно связаны со структурами оседания.

По данным гранулометрического анализа большинство сваренных туфов состоит на более чем 70% по весу из материала с диаметром зерен менее 4 мм. Спайка и кристаллизация зависит, в основном, от относительной температуры и толщины остывающих залежей. Большинство структур сваренных потоков вулканического пепла зависит от температуры и толщины залежи. Спайка начинается со сцепления осколков вулканического стекла и продолжается попутно с уменьшением объема пор и с деформацией составных частей, вплоть до полного сваривания, в результате которого образуется плотное черное стекло.

Кристаллизация накладывается на сваренный материал в любой стадии развития, но степень спайки может влиять на тип кристаллизации. Степень сварки и кристаллизация имеют зональный характер и позволяют различать простой и сложный процесс остывания. Начальная спайка может произойти при температуре ниже 535° по Цельсию, но полная сварка зависит от давления вышележащего материала и от времени, и таким образом зависит от процесса остывания отдельных залежей.

Отложения, образовавшиеся при низкой температуре, такие как "потоки пемзы" Кратерного Озера в Орегоне, в основном, в залежах большой мощности не сварены. Высокотемпературные сваренные туфы из юговосточного Айдахо плотно сварены в очень тонких покровах. Большинство сваренных туфов, вероятно, отложено при средних температурах. Некоторые отложения указывают на систематическое изменение температуры во время цикла извержения, другие указывают на изменения в составе магмы. Существует мнение, что некоторые потоки вулканического пепла генетически связаны с близповерхностными плутонами, некоторые из которых имеют значительные размеры и сложный состав.

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Introduction

...evolution of thought surrounding any ...of scientific knowledge is a fascinating ...t, and none more so than that leading to ...resent concepts of the recognition, origin, ...ode of eruption of the rocks commonly ...welded tuffs or ignimbrites. Many keen ...ists have been troubled or even confused ...e rocks because they show characteristics ...oth tuffs and lavas, but are not clearly ...able to either category.

...this group of rocks belong the "tufflavas" ...Russian Armenia, the "piperno" of Italy, ...lo lavas" and "hai ishi" (ash stones) of ... some of the "rhomb porphyry" of ...way and Sweden, and perhaps the eutaxites ...e island of Teneriffe. We are also finding ...tens of thousands of square miles of ...nic rocks, formerly considered lava flows, ...pyroclastic rocks firmly indurated by weld- ...crystallization of their glassy parts.

...ese rocks are predominantly silicic— ...ites, quartz latites, rhyodacites, and ...s. Andesites and trachytes may occur ...is form, but basalts of this nature are ...ingly rare. As reflected by their com- ...these rocks are, for the most part, ...outed along the orogenic belts, and they ...throughout the geologic column.

...th few exceptions, the rocks in question ...emplaced as particulate flows or pyroclastic ...ches, in contrast to fluidal lava flows ...air-fall pyroclastic rocks. The eruptive ...anism is generally held to be the nuée- ...nte or glowing-cloud eruption in one or ...of its many forms, although some authors ...taken exception to the nuée-ardente ...ion as the universal agent, especially ...elded tuff sheets and "pumice flows" of ...large volume.

...e study of welded tuffs and of their ...elded counterparts is still in its infancy, ...gh major progress is being made, and ...can be expected as quantitative results ...detailed studies become available.

...e importance of these rocks is not limited ...e petrography, petrology, or volcanology. ...concerns the mapping of certain volcanic and metamorphic terrains, with their problems of stratigraphic and structural correlation. It seriously affects the study of calderas, volcano-tectonic depressions, batholiths, and many ore deposits. The geochemist should find welded ash flows a fertile field for innumerable problems of magmatic volatiles, trace elements, and rock alteration. To the experimental geologist they offer unique materials for the study of rate processes, such as welding and deformation of glass, devitrification, diffusion, and cooling.

It would be presumptuous to attempt discussion of all the facets of the welded-tuff problem; some have recently been or will be treated in other papers, and on others little or no work has been done. In this review the writer attempts to outline some of the more promising avenues for future research, as well as to concentrate on those facets of the problem that he feels need special consideration.

The reference list contains only a selection of the available papers on the subject. Many Russian and Japanese publications which might have been included were not available in a language the author reads, and other very good papers were simply not sufficiently germane to the subjects selected for discussion. Most of these are listed in the recently published and nearly complete *Ignimbrite bibliography* by Cook (1959). In addition an excellent summary of eruptive processes and their products has been published by Williams (1957, p. 59–65); a very good summary paper covering many facets of the subject has been published by Martin (1959); and Ross and Smith (in press) present a historical review, summarize criteria for recognition, and discuss microscopic and field features and processes.

Acknowledgments

The writer gratefully acknowledges discussions with numerous colleagues mentioned in the text. Special thanks are due C. S. Ross and R. A. Bailey for reference to our unpublished joint work in the Valles Mountains, New Mexico, and to Bailey for many hours of critical discussion of ideas and facts. Special thanks are

also due P. E. Cloud, Jr., S. S. Goldich, and J. H. Mackin for critical review of the manuscript.

Nomenclature

The writer recognizes that the nomenclature of these rocks is controversial. Differences on terminology are usually resolved when those most concerned reach a common level of knowledge, mutual understanding, and communication. With these thoughts in mind and with the additional thought that the "welded-tuff problem" is, in many respects, still an "infant," it does not seem profitable to discuss the relative merits of different nomenclatures. Instead, for the demands of internal consistency in this paper, the writer will present briefly the usage he has found most applicable to the greater number of deposits of welded tuffs or their nonwelded equivalents. He has no illusions that this usage will necessarily satisfy the needs and beliefs of other workers, nor does he wish to create the impression that it should.

ASH FLOW: The basic unit of ash-flow deposits is the ash flow that is analogous to, or perhaps the same as, the deposit resulting from the passage of one nuée ardente. As defined here, it consists of 50 or more weight per cent of ash and fine ash exclusive of foreign inclusions. Ash (¼ to 4 mm) and fine ash (less than ¼ mm) refer to the Wentworth and Williams' (1932, p. 45) size scale. Most glass shards and crystals are of ash or fine-ash size. The remaining essential materials are pumice lapilli and blocks or, in some types, scoriaceous materials, or mixtures of the two. Most welded tuffs and their nonwelded equivalents fall in this category (*see* discussion of sorting); however, some pyroclastic flows will not conform to the arbitrary 50 per cent minimum for essential particles less than 4 mm in diameter. For these the term lapilli-and-block flows might be used, but as this term is cumbersome, and in view of the fact that the lapilli and blocks can be separated on the basis of their pumiceous or scoriaceous nature, pumice flow or scoria flow (whichever material predominates) seems appropriate, but would call for redefinition of these terms. The term ash flow as used here includes all or, within the limits of the defined particle size, most of the deposits described under the following terms:

Tuff flow
Incandescent tuff flow
Sand flow
Pumice flow
Scoria flow
Block and ash flow (in part)
Gas and ash flow
Hot ash flow
Glowing avalanche (in part)
Deposits of the St. Vincent vertical type (in part)
Deposits of the "Nuée Ardente du katmaienne"
Deposits of the Valley of Ten Thousand Smokes type
Aso lava
Ignimbrite
"Hai ishi"
Tuff lava
Welded tuff
Welded mud lava
Schmelztuff
Piperno
"Shirasu"
Sillar

ASH-FLOW SHEET: Some ash-flow deposits have not been subdivided into well-defined units, yet they are mappable, sheetlike stratigraphic units and are of inferrable ash-flow origin. For these a nonspecific name is used. Ash-flow sheet is used in this sense to include any unspecified sheetlike unit or group of units considered to be of ash-flow origin. If the materials of the sheet are predominantly welded tuff or if it is desirable to emphasize their welded character, the term welded tuff sheet is used.

WELDED ASH FLOW: An ash flow in which welding has produced a conspicuous zonal pattern is termed a welded ash flow.

WELDED TUFF: A welded tuff is a rock or rock body in which vitric particles have some degree of cohesion by reason of having been hot and viscous at the time of their emplacement. Incipient, partial, dense, or complete welding are indicated by these terms. The term welded tuff does not carry a stratigraphic connotation. However, a deposit of welded tuff could conceivably include an entire ash flow, and probably does in some cooling units. The term welded tuff should exclude "fused tuffs" in which reheating of vitric pyroclastic beds in proximity to hot rock bodies was responsible for their coherence. Crystallization may follow or accompany welding but, while common, place, is not essential to that process. Some air-fall materials may be included where welding was in consequence of the inherent heat of the particles.

WELDED TUFF SHEET: A sheetlike body of rock containing conspicuous welded tuff is called a welded tuff sheet. Used loosely it

to any unit or group of units that have en specifically defined.

ING UNIT: A single or multiple ash-flow t (Pl. 1) that can be shown to have gone continuous cooling is a cooling unit. ooling history of the unit may have been ally uniform or broken by successive cements, but not broken to the extent one part cooled completely before another as emplaced on top of it.

Simple Cooling unit is an ash flow or nce of ash flows that has had an essentially rrupted cooling history. Such units re- either nonwelded and noncrystalline cooling or form a pattern of textural . The zonal pattern will be consistent the individual welding and crystallization acteristics of the unit, as determined by variables emplacement temperature, thick- gas content, and physical and chemical position. (*See* section on Zones and Zonal tions.)

Compound Cooling unit is one that shows rtures in the expectable zonation and other perties which result from simple cooling, se the intervals between ash flows were great for readjustment to a single-unit ng gradient (Pl. 2, fig. 1).

MPOSITE SHEET: A cooling-unit complex rades from one cooling unit into two or cooling units is a composite sheet.

ASH-FLOW FIELD: Deposits of pyroclastic consisting preponderantly of ash flows, are related to some specific unit of area, tute an ash-flow field.

Ash-Flow Problem

Within the many-faceted ash-flow problem writer stresses those deposits that contain ed tuffs, especially those that occur in t volume over large areas. The solution of many unsolved problems concerning these s will come about only through detailed dies. Some of these problems are minor , but at least five must be considered major: recognition of ash flows, (2) recognition and nition of units, (3) mode of eruption, (4) ptive vents and source areas, and (5) origin the magmas.

Twenty-five years ago Marshall (1935) and nfield and Ross (1935) discussed the field microscopic characteristics of the New land "Ignimbrites" and the Idaho "welded s." Since that time nearly all authors who e studied welded tuffs in detail have dis- ed problems of recognition, and many have suggested criteria. The problem still remains, however, because the distinction between welded tuffs and lava flows on the one hand, and between ash-flow tuffs and tuffs of other origins on the other hand, is not always possible.

Recognition and definition of units within ash-flow fields is especially important where detailed structural and stratigraphic correlations are sought and where genetic problems are concerned. Deposits that were emplaced virtually "en masse" or from a very rapid sequence of eruptions are much less complex than those that contain cooling breaks or erosional disconformities.

Problems of the mode of eruption are related to the fact that no scientifically observed eruptions are known to have produced welded tuffs or deposits comparable in volume to those resulting from many prehistoric eruptions. Nearly all reasoning of the last 35 years concerning prehistoric deposits has been by analogy with the Valley of Ten Thousand Smokes whose deposits, in turn, have been explained in terms of the nuée-ardente concept developed from the observed eruptions of Pelée and La Soufrière.

The soundness of this chain of reasoning is rarely questioned, although some misinterpretation of the classical concepts have been published. Nevertheless, the eruption mechanisms before emplacement of deposits from "nuées ardentes" need investigation and clarification as does the precise meaning for the term nuée ardente, if we persist in using the term to designate the agent of emplacement of these deposits.

The most important ash-flow problem concerns the location and kind of eruptive vents and source areas which produce the sheet deposits of great volume. It seems almost incredible that, of the hundreds of occurrences of ash flows comprising tens of thousands of cubic miles of rock in the western United States, for example, the number of unequivocally known source areas is probably less than 10. In terms of published data the number is 4. These are all subsidence structures: Crater Lake caldera, Oregon; Valles caldera, New Mexico; Creede caldera, Colorado; and parts of Yellowstone National Park. On the other hand, practically all the deposits of "welded tuffs" or "pumice flows" known to have a volume of more than a few cubic miles and that have been unequivocally related to their source areas are related to subsidence structures. With this evidence favoring subsidence in the source

areas, it becomes of prime importance to locate these sources for the older deposits.

The question of origin of magma is of special interest in pyroclastic eruptions producing ash flows, because some ash-flow deposits are very large and are located in tectonic settings that suggest kinship with granitic batholiths. The problem concerns the immediate origin of the magma from "volcanic" or "plutonic" sources rather than its ultimate origin.

Mode of Eruption

General Statement

Present concepts of the mode of eruption of hot pyroclastic flows center around the nuée-ardente or glowing-avalanche eruption and depend almost entirely on the well-known published accounts of the 1902 eruptions of Mt. Pelée in Martinique (Lacroix, 1903a; 1903b; 1904; Anderson and Flett, 1903) and La Soufrière on St. Vincent (Anderson and Flett, 1903), and the eruption in 1912 near Mt. Katmai in the Valley of Ten Thousand Smokes, Alaska (Fenner, 1923). These accounts have been augmented by detailed observations of the 1929–1932 eruption of Pelée by Perret (1935) and by various eruptions of Merapi (1930–1935) in central Java (Stehn, 1936; Neumann van Padang, 1933; Van Bemmelen 1949). More recent eruptions, among which were those from Lamington (1952) in New Guinea (Fisher, 1954; Taylor, 1954; 1956) and Mibok-Hibok (1948–1953) in the Philippines (MacDonald and Alcaraz, 1956), have tended to confirm and strengthen the correctness of earlier observations.

There is thus a body of data from several competent observers which makes the "nuée ardente," in at least some of its forms, well known.

Opinion is divided, however, as to whether or not nuée-ardente mechanics are adequate to explain the eruption and emplacement of the pyroclastic materials that sometimes form welded tuffs. It may be significant, in this regard, that no observed nuée ardente has formed a recognized welded tuff. Because of the divided opinion and because some of the existing concepts of "welded-tuff" emplacement seem traceable to misconceptions regarding the classical nuées ardentes and to ambiguous usage of the term, it seems necessary to inquire briefly into the nature of the classical nuées ardentes. This is also important for understanding the development of the "pyroclastic-flow" concept.

Nuée Ardente

Lacroix (1903a) introduced nuée ardente as a geological term for the devastating eruption of Mt. Pelée on May 8, 1902, and for subsequent eruptions from Pelée. The eruption on May 7, 1902, of La Soufrière on St. Vincent also came to bear the name nuée ardente, as have many other eruptions from other volcanoes in other parts of the world, particularly Merapi in central Java.

Nuée ardente has also been used to designate eruptions which are believed to have been responsible for the great welded-tuff sheets and their nonwelded counterparts which are the main subject of this paper. This usage of nuée ardente has its origin in the studies of Fenner (1923), Lacroix (1930), and others, although Fenner sensed the fundamental differences between the deposits of the Valley of Ten Thousand Smokes and those of Pelée.

It should now be recognized that most welded ash flows cannot have had an origin from an eruption of the type that occurred at Mt. Pelée in 1902. The very size of the deposits precludes this; however, the mechanics of eruption and transport as deduced by the observers of the deposits of the eruption of Pelée and La Soufrière that took place on May 7 and 8, 1902, and observers of subsequent eruptions from Pelée, together with Fenner's interpretation of the deposits of the Valley of Ten Thousand Smokes, give us insight into a probable mechanism for eruption and transport of the ash-flow deposits of large volume.

All observers of the nuée ardente phenomenon except possibly Lacroix, agree that the nuée ardente has two parts—a basal avalanche and an overriding spectacularly expanding cloud of gas and dust (Lacroix, 1904, p. 350; Anderson and Flett, 1903, p. 447–453; Perret, 1935, p. 5; Neumann van Padang, 1933, p. 134; Van Bemmelen, 1949, p. 191–192; Taylor, 1954, p. 86; Akkersdijk, 1941, p. 63–64). The distinction between the two parts has not always been sharply drawn. These statements refer to the nuée ardente as an agent of transport of material from the vicinity of the vent to its final resting place, not to the material as it is being erupted from the vent.

Lacroix (1904, p. 350) has described the nuée ardente:

> [illegible]pe nuée ardente est constituée [illegible] de matériaux solides dans un m[illegible] et de gaz à haute température. [illegible]ici je ne reviendrai pas. La [illegible]sions qu'elle présente au mome[illegible] carapace du dôme montren[illegible]ise sous celle-ci à une compressi[illegible] au bout de quelques secondes [illegible]me supérieur de plusieurs mill[illegible] qu'elle possédait lors de son d[illegible] à la base, se trouve une zo[illegible]rature, dans laquelle prédom[illegible]ux solides (blocs de toutes di[illegible]s plus petits, cendres fines) [illegible] ou des particules solides qu[illegible]me de la chaleur et doit être en[illegible]sphère de gaz et de vapeur [illegible]rimée au début, mais se dilate [illegible] cette atmosphère qui, empêcha[illegible] de se toucher, maintient l'en[illegible] de mobilité lui permettant de [illegible], presque à la façon d'un lie[illegible]
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> Probably because of the trajec[illegible]) nature of the May 8 nu[illegible] in its early stages of form[illegible] aware of but did not emph[illegible]lanche; he was, rather, pr[illegible] "blast" or "cloud." Here[illegible] roots of the "airborne-cloud [illegible]ich permeate the literature on [illegible]mbrites. Many writers have [illegible]ds as the agents of transport [illegible]erials. This is doubly confu[illegible] realized that the cloud [illegible]es ardentes does carry and [illegible], although in insignificant [illegible]mpared to the avalanche por[illegible] Anderson and Flett (1903, p. [illegible]ing seen the trajectoral-typ[illegible] the following account of [illegible]ption of Pelée:
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> Then in an instant a red-ho[illegible] the cleft in the hillside, and [illegible]ntain slopes right down to th[illegible] and in it were brighter st[illegible]ght were large stones, as the [illegible] tails of yellow sparks. The[illegible]rently rebounding when they [illegible] the ground, but never rising hi[illegible] mass of the avalanche was [illegible]urface was billowy like a cauld[illegible]. Its velocity was tremendo[illegible] on the mountain top did n[illegible] clearly how the fiery avalan[illegible] perfect view of its cour[illegible]s of the hill, and its glowing [illegible] clearly seen. Its similarity [illegible]lanche was complete in all re[illegible]perature of the respective ma[illegible]ed in a minute or two, and in [illegible] rushing forward over the sea[illegible]ing cloud, black, and filled w[illegible]e straight out of the avalanc[illegible]ly only the lighter and cooler

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s de se toucher, maintient l'ensemble dans un
de mobilité lui permettant de couler sur les
es, presque à la façon d'un liquide."

Probably because of the trajectoral (directed-
) nature of the May 8 nuée ardente, at
in its early stages of formation, Lacroix
aware of but did not emphasize the basal
lanche; he was, rather, preoccupied with
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ds as the agents of transport of "avalanche"
terials. This is doubly confusing when it is
realized that the cloud portion of the
es ardentes does carry and deposit ash and
although in insignificant amounts as
ared to the avalanche portion.
Anderson and Flett (1903, p. 494–495), not
ing seen the trajectoral-type nuée ardente,
the following account of a July 9, 1902,
tion of Pelée:

"Then in an instant a red-hot avalanche rose
the cleft in the hillside, and poured over the
ain slopes right down to the sea. It was dull
and in it were brighter streaks, which we
ght were large stones, as they seemed to give
bits of yellow sparks. They bowled along,
ently rebounding when they struck the surface
e ground, but never rising high in the air. The
r mass of the avalanche was a darker red, and
surface was billowy like a cascade in a mountain
k. Its velocity was tremendous. The mist and
on the mountain top did not allow us to see
clearly how the fiery avalanche arose, but we
a perfect view of its course over the lower
s of the hill, and its glowing undulating surface
clearly seen. Its similarity to an Alpine snow
lanche was complete in all respects, except the
perature of the respective masses. The red glow
d in a minute or two, and in its place we now
rushing forward over the sea, a great rounded,
ng cloud, black, and filled with lightnings. It
e straight out of the avalanche, of which it was
ly only the lighter and cooler surface, and as it advanced it visibly swelled, getting larger and larger every minute."

Of the avalanche deposits formed from the May 7 eruption from Soufrière, Anderson and Flett (1903, p. 449) write:

"The geological evidence was not sufficient to demonstrate what form the discharge took, what was its path, and how great was its velocity when it left the crater; but by the time it reached the valleys below it was a rushing torrent of sand, stones, and hot gases, which coursed along the valley bottoms, adapting itself readily to all changes in their configuration, too heavy to surmount any great height, but sweeping over the surface of the minor ridges, and coming gradually to rest in the deep ravines behind them. In the valleys of the Wallibu and Rabaka Dry River it filled the whole channel, and when its energy was spent it lay in banks, with irregular rounded upper surfaces, like glaciers of black sand. In the more shallow and open valley of the Wallibu Dry River it had not been confined to a narrow and steep-sided channel, but had been free to spread out laterally, and there it took the form of a broad sheet of sand with round-backed ridges, like wreaths of snow, pointing down the valley and diverging with a slightly fan-shaped arrangement."

These observations give a very clear picture of the avalanche portion of the nuée ardente. After comparing their observations at Soufrière with those at Pelée, they summarized in part that Pelean-type eruptions are characterized by avalanches of incandescent sand accompanied by a great cloud of gas and dust. The avalanche and the cloud both move at high velocity.

Anderson and Flett believed that the nuées ardentes moved under the influence of gravity, while Lacroix, although recognizing that gravity played a part, believed that a directed initial explosion was also necessary. They agreed that the extreme mobility of the mass was due to expanding gases.

The controversy was slowly resolved when, through observations of other nuée-ardente eruptions, it was realized that the position of the vent within the volcanic edifice influenced the initial behavior of the nuée ardente. It is not necessary to review the details of this evolution here; it is revealed in the works of Perret (1935), Lacroix (1908; 1930), Escher (1933a; 1933b), Stehn (1936), Grandjean (1931), Neumann van Padang (1933), Kemmerling (1932), and MacGregor (1952; 1955). MacGregor's paper is really the first detailed analysis of the problem, and in it many distinctions are clearly drawn. In particular it points up a number of common misconceptions as well as specific published errors.

Fenner (1923, p. 71–74), from his studies in the Valley of Ten Thousand Smokes, concluded that neither gravity nor violent initial explosion, alone, could explain the distribution of the "sand flow," and that a third factor was essential. He writes (p. 74):

"This, as I conceive it, is the self-explosive property inherent in the magma itself, due to the presence and evolution of dissolved gases; and this explosive evolution is not manifested immediately, but is prolonged over a considerable portion of the time during which the spreading movement continues, and gives to the material its fundamental characteristics of quasi-liquidity. Gravity plays an important part in directing the flow down mountain slopes or along topographic depressions, but it is believed that its effectiveness would be rather insignificant were it not for the peculiar properties imparted by the form of disintegration described."

We thus see Fenner as the originator of the "auto-explosive" flow concept. Lacroix, and Anderson and Flett recognized the fundamental importance of expanding gases in giving the mass its high mobility, especially over low gradients, but the delayed or continued evolution of gas has been more clearly expressed by Fenner.

Perret (1935), who witnessed more than 100 nuées ardentes from Pelée between 1929 and 1932, clearly recognized their dual character. His concept of the flowage mechanism was not essentially different from Fenner's. He stressed their wide range in intensity. Van Bemmelen (1949, p. 191–192) summarizes the nuée-ardente phenomenon based on his and other workers' observations in Indonesia, principally from the Merapi volcano in Java. He points out that the character of the eruption changes with an increase in volume of erupted material. Small-volume avalanches may be accompanied by a dust cloud, whereas larger volumes of more than a thousand, up to many hundreds of thousands of cubic meters, give rise to a nuée ardente of dual character. The "ladu" (avalanche) follows the canyons, whereas the "nuée ardente" may jump the banks and become independent of the avalanche for short distances.

The usage of the term nuée ardente is ambiguous. Within the references cited in this section it has been used for (1) the eruption which produces the laterally moving mass of fragmental material and gas, (2) the avalanche and overriding cloud as agents of transport, and (3) the cloud, exclusive of the avalanche.

Seemingly the nuée ardente as an agent of transport of volcanic materials, whatever it may be at the moment of its emergence from the vent, is, when it begins to leave a recognizable deposit, a flow of pyroclastic materials in which the fragments are hot and are emitting gas. An accompanying expanding cloud of gas emerges from the flow and carries considerable solid material, and it may become separated from the flow because of topographic diversions and run a short distance (several miles) on its own, before the gas becomes separated from the solid particles. The cloud may deposit thin beds of ash.

Any argument about the unity or separateness of the avalanche, or flow, and the cloud must center around the degree of inflation of the flow or the sharpness of transition between the flow and the cloud. Some writers have envisioned the entire nuée ardente as a "cloud" with gas suspending the solid materials, the whole having a dense base grading up to a diffuse top. Such a medium should, in spite of turbulence, leave a graded deposit either vertically, laterally, or both. To the writer's knowledge no such deposits have been described.

The eruptions discussed in this section were insignificantly small compared to ancient ash-flow eruptions. To reconcile the two we must magnify the nuées many fold or seek another explanation for the emplacement of ancient deposits.

Perhaps the significant point of difference between Pelean eruptions and eruptions that produce welded ash flows, aside from composition or the character of the vent, is that the entire mass of a Pelean nuée ardente is produced in one short burst, whereas the other type is produced by continuous evolution of material over periods of hours, days, or perhaps weeks. Fluctuations in intensity of the eruption allow diversity in ash flows not seen in Pelean deposits. The difference is probably directly related to the volume of eruptible material.

Vertical Component

The concept of formation of pyroclastic flows from vertical-eruption columns has not been given the consideration it deserves*. To

* Since this manuscript was submitted, two important papers have come to the writer's attention:

Hay, R. L., 1959, Formation of the crystal-rich glowing avalanche deposit of St. Vincent, B. W. I.: Jour. Geology, v. 67, p. 540–562

Taylor, G. A., 1958, The 1951 eruption of Mount Lamington, Papua: Australia Bur. Mineral Resources, Geology and Geophysics Bull. 38, 117 p.

Hay's findings at Soufrière are so pertinent to the discussion of the vertical component and its probable influence on cooling and sorting that the author

the concept embodied in Lacroix's p. 421–472) *nuée ardente d'explosion* and the *nuée ardente du massif du* calls for vertical eruption, but to nearly the vertical component is just suffi- boost frothing magma to the crater's hence it begins its lateral journey as a ardente." Perhaps the most important of erved historical eruptions shedding light problem was that of Komagatake in Kozu (1934, p. 136) states that during part of the eruption pumice was straight up as high as 12 km. This was deposited in well-stratified beds; it was carried by the winds for more 00 km. This air-fall pumice was followed ge vertical-eruption columns containing quantities of pumice erupted to lesser than the earlier materials. This later fell back on the mountain and poured the valleys to distances as great as 6 km. massive column of pumice above the together with the pumice flows pouring the mountain, may be seen in one of illustrations (Kozu, 1934, Fig. 20). ams (1942, p. 79) visualized conditions ter Lake, during the eruptions of the ce flows," to be much the same as at atake in 1929. Similar deposits were ed, but they are of quite different order nitude.

Komagatake "pumice flows," according t (1938, p. 1851), were dry avalanches ches seches, Lacroix, 1930) and are not rable to deposits such as the Bishop tuff. sense this may be true, but it may be that, of all pyroclastic flows produced erved eruptions, the ones most closely us to deposits of Crater Lake, Krakatoa, Valley of Ten Thousand Smokes are magatake "pumice flows." The Komaga- lows were of very small volume, erupted vertical column and hence somewhat by mixing with air before the flows were d. Yet fumarole temperatures as high as were measured in deposits averaging 10 feet thick.

Bishop tuff is locally more than 500 feet and has a volume of more than 2400 times the Komagatake deposits. This alone is ly significant with regard to the ultimate but not with regard to mechanics of cement. Units of the Bishop tuff that are only 10 feet thick probably show no high-temperature characteristics that are not shown by the Komagatake flows, and, aside from compositional differences, the two would probably be indistinguishable. This is not to imply that the two deposits were emplaced at the same temperature, but rather that comparisons are not meaningful unless units of equal thickness are found to be different.

That the pyroclastic flow is a heat-conserving mechanism is shown by the temperature measurements on some historic deposits and by the existence of welded tuffs. Boyd (1957, Ph.D. Thesis, Harvard Univ.), in his study of the Yellowstone welded tuffs, has concluded from a careful analysis of factors causing heat loss, both during emplacement of the tuff and in the conduit, that the formation of welded tuff, from material emplaced by the "tuff-flow" mechanism, is thermodynamically feasible.

Boyd's calculations assume minimum mixing with air and indicate a temperature loss of less than 5° C., if the emplacement time was 1 hour, or less than 45° C., if the emplacement time was 10 hours. The approximate correctness of these figures, for the ideal ash flow, is suggested by the existence of certain welded-tuff sheets that are densely welded to within a few feet of their tops. Such a condition calls for very efficient heat conservation, because it means that the glassy particles must deform and weld under a very low load of less than a few pounds per square inch. Temperatures necessary to accomplish welding at such low loads are probably in excess of 800° C. (Smith, Friedman, and Long, 1958), whereas the eruption temperature of rhyolitic magma containing phenocrysts must be below about 960° C. and is probably below 900° C. for most rhyolitic pyroclastic rocks. These figures are suggested from a consideration of Tuttle and Bowen's (1958, p. 58) PT curve for the ternary minimum, and from our knowledge of minimum water contents of volcanic glass (about 0.1 per cent). There is no need to develop this argument here. It is mentioned only to show that field and experimental evidence support Boyd's conclusions that actual heat loss during flowage is small for ideal ash flows and that heat conservation is very efficient.

The ash flow seems in fact to be so efficient a heat-conserving mechanism that the writer is inclined to think that, except for eruptions from domes, the only reason ash flows containing a high proportion of glass ever escape welding is because they were cooled between the time they were erupted from the vent and

recommends that Hay's paper be read by seriously interested in these facets of the problem.

e time they began their journey as pyroclastic flows. Seemingly the only significant cooling mechanism that can be invoked for this interval is mixing with air in a vertical-eruption column; the amount of mixing or degree of cooling is dependent on the height, density, and mechanics of the column, or columns.

Seeking an explanation for Lacroix's "lateral blasts" at Pelée in 1902, Jaggar (1902, p. 366) suggested that they were due to the interference between downfalling ejecta and the upblast from the crater. The interference caused the material to be deflected laterally. Anderson and Flett (1903, p. 513) discounted Jaggar's theory on the grounds that it fails to account for their observations of subsequent eruptions from Pelée. These and later observations by others at Pelée and other volcanoes support the views of Anderson and Flett, and it seems clear that Jaggar's explanation is precluded for eruptions from domes, which, because of the position of their vents, give sectoral distribution and commonly have a horizontal component. However, it is extremely doubtful whether Jaggar's or a similar explanation has been or can be disproved for the 1902 eruption from Soufrière. The important point of Jaggar's explanation is that it demands a vertical column of pyroclastic material and gas.

If the amount of solid material in the column exceeds that which can be efficiently erupted as air-fall pyroclastics, the excess must be displaced laterally as pyroclastic avalanches. Whether this laterally displaced material is influenced more by interference between upsurging and downfalling material, or whether it is related to differential velocities in the column or some other mechanism is an important point, but probably not so important as the thought that the volume of solid material in the column is a function of gas pressure, and that fluctuations or systematic changes in gas pressure might effectively control the amount of, and the emplacement-temperature characteristics of, the laterally displaced material. Such a scheme allows us to envision an eruption column which at one stage is producing air-fall pyroclastics and at another stage is simply boiling fragmental material over the lip of the vent.

Behavior of the laterally displaced material should depend on its volume, temperature, gas content, and the surrounding topography. If its volume and temperature are low, the material may accumulate to form dry avalanches, *avalanches seches* of Lacroix (1930, p. 466) or "hot avalanches" of Perret (1924, p. 90). If its volume is large but its temperature is low, it will perhaps form deposits like those around Crater Lake, Oregon. If its temperature is high and volume variable, it will form welded tuff sheets, the characteristics of which will be determined by temperature, thickness, gas content, and composition.

The discussion in this section implies that the emplacement temperature of these pyroclastic flows may be controlled to much greater degree by cooling in a vertical column, before the flows form, than by a fundamental difference in magma temperature or initial gas content, and that this cooling is primarily related to the volume of materials in the column, the height of the column, and perhaps the nature of the vent. This is not to infer that the magma temperature is constant; it is not, and some deposits record a systematically changing temperature.

Emplacement by Flowage

The geologic evidence, aside from observed nuées ardentes, for the emplacement of ash flows by flowage or avalanche mechanics has been cited by authors such as Fenner (1923, p. 61–74), Anderson and Flett (1903, p. 449), Williams (1942, p. 81), and Matumoto (1943, p. 3–4). It may be summarized as follows: (1) restriction of deposits to valleys or other topographic lows in mountainous regions; (2) nearly level upper surfaces over buried topography except where compaction because of welding has caused surface irregularities; (3) lack of sorting far from vents which would suggest emplacement *en masse* rather than by air fall; (4) flowage features in some deposits; (5) retention of heat for long periods of time (years) resulting in fumarolic activity, welding, and crystallization, which appear improbable in air-fall deposits; (6) incorporation of surface debris.

TOPOGRAPHIC RESTRICTION. Restriction of ash-flow deposits to topographic lows is well illustrated by the Crater Lake "pumice flows." Williams (1942, p. 81) comments that the outstanding feature of these deposits is the manner in which they have followed the principal canyons near Crater Lake. In the Valles Mountains, New Mexico, all canyons that descend from the high-mountain source area and that are older than the Bandelier rhyolite contain welded ash flows. These flows coalesce to form continuous sheet deposits on pediment and alluvial surfaces below the canyon mouths (Ross and Smith, in press).

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...logic evidence, aside from observed ...ntes, for the emplacement of ash ...lowage or avalanche mechanics has ... by authors such as Penner (1921, ...Anderson and Flett (1903, p. 449), ...1942, p. 81), and Matumoto (194... It may be summarized as follows: ...ion of deposits to valleys or other ...c lows in mountainous regions; (2) ...d upper surfaces over buried topog... ...ept where compaction because of ...s caused surface irregularities; (3) ...tting far from vents which would ...placement *en masse* rather than by ... flowage features in some deposits; ...on of heat for long periods of time ...lting in fumarolic activity, welding, ...llization, which appear improbable ...eposits; (6) incorporation of surface ...

...TRIC RESTRICTION. Restriction of ...posits to topographic lows is well ...y the Crater Lake "pumice flows." ...942, p. 81) comments that the out... ...ture of these deposits is the manner ...hey have followed the principal ...r Crater Lake. In the Valles Moun... Mexico, all canyons that descend ...gh-mountain source area and that ...ah the Bandelier rhyolite contain ...lows. These flows coalesce to form ...sheet deposits on pediment and ...aces below the canyon mouth ...mith, in press).

...contrast to the coalesced sheets on the ...flanks of the Valles Mountains, the "Aso ... (Matumoto, 1943, p. 3–4) form a con... ...us field peripheral to the caldera, whereas ...er levels the field is divided into innumer... ...branches that follow the highly dissected ...raphy.

...LL SURFACES. The nearly level upper sur... ...of ash-flow sheets whose bases may rise ...fall in response to changes in topography ...well known and need no further discussion.

...K OF SORTING. Lack of sorting has been ...ed as a characteristic feature and criterion ...recognition of ash flows. It is generally be... ...d that the lack of sorting is a result of ...ation from a turbulent flow or avalanche, ...although some air-fall deposits in the vicinity ...eruptive vents may also give rise to nonsorted ...ll deposits, and at times the two are indis... ...ishable (Williams, 1957, p. 64).

...ically many ash flows do show some sort... ...especially near their distal ends, where it ...be presumed that they were moving more ...owly before coming to rest. Such sorting ...ems to be related directly to flowage and in ...rcular to some measure of laminar flow, ...d its visible traces are discussed under ...mary flow features.

...LOWAGE FEATURES. Flowage features are of ...types, primary and secondary.

...Primary flow features include:

...(1) Pumice swarms—discontinuous streaks ...lenticular accumulations of pumice lapilli ...d blocks in a finer matrix (Taneda, 1954, p. ...; 1957, p. 96; Taneda, Miyachi, and Nishi... ...1957, p. 113).

...(2) Rafted pumice—top, side, and flow-front ...cumulations of pumice blocks (Kuno, 1941, ...146; Ross and Smith, in press).

...(3) Inclusion trains—discontinuous streaks ...lenticular accumulations of accidental inclu... ...(Kuno, 1941, p. 147).

...These primary flow features appear to be ...t abundant near the distal portions of ash ...where they seem to be related to lowered ...ity movement before the ash flow comes ...rest. Surface accumulations of pumice, ...ing flow tops, probably are more common ...generally recognized and may at times be ...of in distinguishing individual flows in ...ely welded tuff deposits. These flow ...ures may be overlooked in welded tuffs, ...ere welding and crystallization tend to ...ure them.

...ondary flow features are:

...(1) Radial stretching—shards and particu... ...pumice fragments may occasionally have been squeezed during compaction and welding beyond simple loss of pore space, resulting in radial stretching of the fragments. Most pumice fragments in densely welded tuffs have simply collapsed without elongation; however, if under great load or high temperature, they occasionally display abnormal elongation in cross section. Ross and Smith (in press) have suggested that secondary solution of volatiles by pumice may cause slight viscosity differences between shards and pumice fragments and may allow preferential radial elongation of pumice by differential compaction. Probably most pumice fragments in ash flows before welding are not longer than three times their smallest dimension. Taking porosity and preferred orientation into account, Ross and Smith (in press) suggest that, after dense welding, collapsed pumice fragments having a vertical dimension 3 to 20 times smaller than their long dimension are probably the result of simple loss of pore space without elongation. An elongation of 20 to 60 or more times the smaller dimension is believed to indicate stretching.

(2) Flowage deformation—the stretched pumice fragments are disclike in plan view and have random orientation. Some welded tuffs, however, contain stretched pumice that has preferred orientation, and these seem to indicate mass flowage during or after welding. In examples of this type seen by the writer the distance flowed could have been only a few inches or at most a few feet.

Secondary flowage in these rocks is of minor importance to the entire problem. It may be related to sliding off topographic highs or earth movements during welding of the tuff.

HEAT RETENTION. Retention of heat, resulting in welding and crystallization, is one of the strongest arguments for the emplacement by flowage of welded tuff deposits. Heat measurements on historic ash-flow deposits are few, but significant. Unfortunately all the temperature measurements on the "sand flow" in the Valley of Ten Thousand Smokes were of necessity made on fumaroles, rather than in the ash itself, and the first of these not until 5 years after the eruption. Fumarole temperatures, however, may approximate the internal heat of the flow, although variables such as gas reactions, localization of gas in joint cracks, depth from point of origin of the gas, and thickness of the flow all make an accurate heat analysis impossible or, at most, very undependable.

Because of the still unresolved controversy over the possibility of a deeper-seated source

for some of the fumaroles, the most significant temperature measurements in the Valley of Ten Thousand Smokes probably are those made on fumarole no. 1, near the distal end of the flow. These are also the only ones that span a 2-year period, and they give some indication of the rate of cooling and of minimum emplacement temperature. They are shown in Figure 1 along with all other temperature measurements made on fumaroles that Allen and Zies could identify in 1919 as the same ones measured in 1918 by Sayre and Hagelbarger (1919, p. 262–278). All but three of these measurements show a temperature drop similar to that shown by fumarole no. 1. The three that show a rise in temperature are unexplained. The maximum temperature measured among the fumaroles was 645° C. (Allen and Zies, 1923, p. 101). If this temperature, 7 years after emplacement of the ash, is unrelated to a deeper source, it certainly must reflect a very deep layer of ash.

Also shown in Figure 1 are cooling curves drawn from measurements of both fumaroles (*S* curves) and the pumice flow deposits (*P* curves) formed during the eruption of Komagatake in 1929 (Kozu, 1934, p. 143). The curves labeled *P* are three of five very similar curves that show the rate of cooling in the pumice at a depth of 70 cm and give a minimum emplacement temperature of 385° C. The curves labeled *S* were made on fumaroles; the maximum temperature of 510° C., measured 8 to 11 days after the eruption, may be close to the maximum emplacement temperatures of the flows.

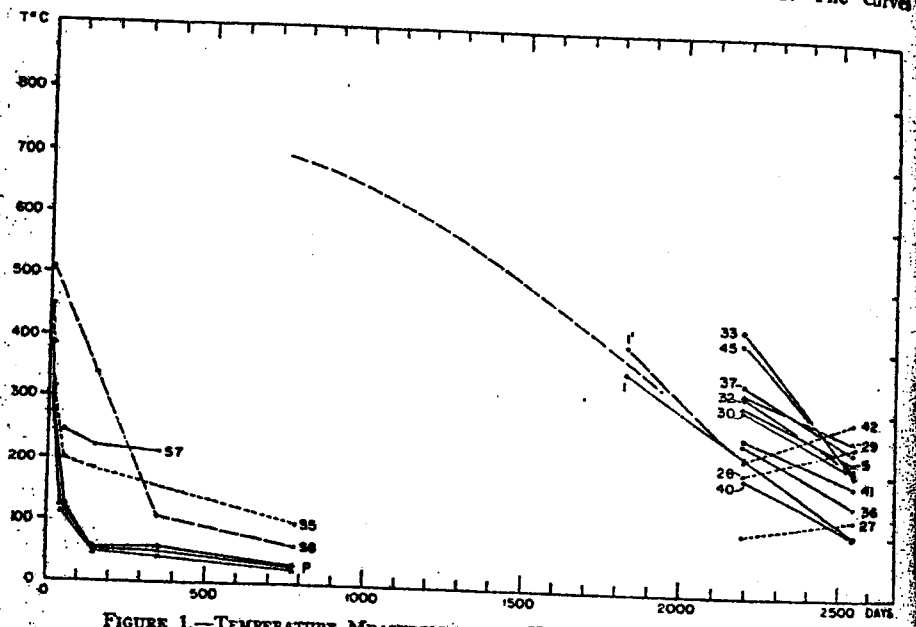

FIGURE 1.—TEMPERATURE MEASUREMENTS ON HISTORIC ASH-FLOW DEPOSITS

Komagatake pumice flows—data from Kozu (1934, p. 143): *S* curves—fumaroles, *P* curves—body of pumice. Valley of Ten Thousand Smokes sand flow—data from Allen and Zies (1923, p. 106); Zies (1929, p. 34); and Lovering (1957, p. 1590).

INCORPORATION OF SURFACE DEBRIS. It is not unusual to see in ash flows inclusions that could have been derived only from the surface over which the ash flow traveled. The inclusions range from very fine-grained material to boulders weighing tons. Some writers have observed evidence suggesting a strong erosive power of ash flows (Tsuya, 1930, p. 252). The ash flows constituting the Bandelier rhyolite tuff of New Mexico have locally swept the underlying surface clear of rock debris of all kinds and sizes up to boulders several feet in diameter, whereas elsewhere the flows have passed over bedded air-fall ash deposits seemingly without disturbing even the finest particles. In those places showing evidence of erosion the determining factor apparently was an irregular ground

surface which increased turbulence in the overriding mass.

Particulate or Foam (Froth) Flows

For at least some "welded tuffs" several writers have proposed mechanisms of emplacement which differ from the pyroclastic-flow concept. It has been suggested that emplacement occurred either as a mass of coherent foam which subsequently collapsed to give "welded-tuff" textures, or as a gas-charged lava which vesiculated and fragmented top and bottom while flowing, resulting in a sort of pseudo "welded-tuff" deposit in which the dense interior of the flow is really a nonfragmented, but vesiculated and collapsed lava.

Kennedy casually (1955, p. 495) suggested the first mechanism for the origin of the vast welded-tuff sheets of the Yellowstone area. Boyd (1957, Ph.D. Thesis, Harvard Univ.) from field and laboratory data, believes the evidence favors the particulate-flow concept; he suggests, however, that one local unit in Yellowstone Park, the Canyon flow, may have originated as proposed by Kennedy.

Hausen (1954) concluded that the Dorena "welded tuff" of western Oregon was emplaced as a vesiculating lava flow. Top and bottom of the flow were fragmented, forming what seems to be typical "pumice tuff," but the interior was never disaggregated. The eutaxitic structure (Hausen, "welded fusion structure"), according to Hausen, was formed by "flowage along planes of minute vesicles within the partially crystallized lava." Petrofabric study of the biotite lineation in the dacite "welded tuff" (Hausen, 1954, p. 212–213) shows a preferred orientation in the dense interior of the mass, but a less well oriented to random distribution in upper and lower parts.

Hentschel (1955, p. 142) invokes a third mechanism for explaining "welded tuffs." This mechanism involves vesiculation and fragmentation of the magma at some depth without immediate eruption, followed by regeneration ("generierte") to a melt, and finally by eruption as nonhomogenized lava flows. This interesting concept seems to be within the realm of possibility for small aberrant deposits but might be expected to obliterate the typical pyroclastic structure of welded tuffs. It might give rise to a streaky, banded flow rock which would have all external characteristics of a true lava flow. The mechanism is conceivable in view of the existence of pyroclastic dikes and the possibility that such material could have been extruded *en masse* under optimum conditions.

This concept also is analogous to one held by Iddings as a mechanism for the formation of "welded pumice." Iddings (1909, p. 331) envisioned the extrusion as a lava flow of previously erupted fragmental materials that had fallen back into a vent and been reheated. He also explained flow breccia by this mechanism. Ross and Smith (in press) discuss this and other mechanisms of formation of the rocks Iddings called "welded pumice."

The controversy over the classical Armenian "tufflavas" and the Italian "piperno" has been discussed by Zavaritsky (1937, p. 15), who agrees with Paffenholz (1938) that the "tufflavas" are of pyroclastic origin, and with Dell'Erba (1892) and Zambonini (1919) that the Italian "piperno" was also a pyroclastic rock. Both "tufflavas" and "piperno" are regarded as lava flows by other authors (*e.g.*, Levinson-Lessing, Kalkovsky, and Abich, as cited by Zavaritsky).

Summary Statement

The evidence from published studies of welded tuffs overwhelmingly favors emplacement by avalanche or flowage of fragmental material and hot gas. None of the other proposed mechanisms has been convincingly demonstrated even for a minor deposit.

The development of the alternate theories for emplacement of welded tuffs however in part probably resulted from the reluctance of geologists (Grange, 1934; Kennedy, 1955; Hausen, 1954; Hentschel, 1955) to accept the "air-borne cloud" origin. This concept was an unfortunate misinterpretation of the mode of emplacement of nuées ardentes that undoubtedly was influenced by the devastating effects of the eruptions.

During the eruption of May 8, 1902, at Pelée it was the cloud that devastated St. Pierre and left behind ash and lapilli deposits up to a few feet thick (Anderson and Flett, 1903, p. 487). The avalanche from which the cloud was derived was probably confined to the valley of the Rivière Blanche. During the eruption of May 7, 1902, at Soufrière clouds caused the death and devastation of the settlement on both sides of St. Vincent and deposited a few inches of ash (Anderson and Flett, 1903, p. 448). The avalanches from which the clouds were derived were confined largely to the Wallibu and Rabaka valleys.

It has not been shown that a welded tuff

for and ever form from the ash cloud. The size and temperature of Pelean-type clouds are probably inadequate. However, if we assume that clouds accompanied prehistoric ash flows, as they probably did, conceivably they were at times hotter and larger and may have carried more ash. If the glassy ash could have been *emplaced* at temperatures of the order of 900° C., it would most surely develop incipient or partial welding. Complete welding would depend on the thickness of the deposit. Such welded-tuff deposits, if they exist, might have interesting distributional and textural characteristics, but would be very subordinate in volume to the total products of the eruptions which produced them.

The supporters of the particulate-flow mechanism generally agreed that the driving force of the ash flow or avalanche is gravity, aided by expanding gases. Herein lies a problem that needs solution, namely, what is the true nature of the gas-emission process, and how does it vary in different ash flows? Is total vesiculation confined to the vent, conduit, or chamber, or does some of it take place in the flow, and, if so, how much?

If we assume that some vesiculation takes place during flowage, then gas is emitted from the flow in several ways: (1) release by vesiculation during flowage, which, if explosive, gives rise to the so-called "auto-explosive" property discussed by Perret (1935, p. 22–24) and Fenner (1923, p. 74); (2) escape of gas that was trapped by the sheer bulk of the ash and pumice, but which had been released by vesiculation before the flow formed; (3) rupture during flowage of vesicles that contain partly expanded gas; and (4) diffusion from the glass shards and pumice. Process (4) should take place as long as the glass remains oversaturated with respect to the temperature and pressure of its immediate environment but would not be "auto-explosive" in the strict sense. Vesiculation, especially in the vent, probably does not reduce the glass to a state of saturation or undersaturation, and the glass may continue to lose gas even after some cooling. If the amount given off by diffusion were only a few hundredths of a per cent by weight, the volume at the eruption temperature would be impressive and would provide an adequate lubricant.

This interplay of possible mechanisms could be important in determining the physical character of the final pyroclastic material. Some insight into the problem may be gained from statistical analysis of pumice and shard types, and of sorting characteristics. For example, many ash-flow deposits contain quantities of pumice crowded with long fine, parallel to subparallel, tubular vesicles, and the shards may be seen to have formed by fragmentation of such pumice. Presumably the only place such pumice could form is in the conduit, and this suggests that most, if not all, vesiculation, together with much loss of gas, took place before the ash flow was formed. The lubricating gas of the ash flow, then, must be attributed to mechanisms other than auto-explosion in the strict sense. Some ash flows, however, show a paucity of long-tube pumice, and the shards are coarse irregular fragments, many with spherical vesicles. Other deposits are mixtures of types. Quantitative studies of shard and pumice types have not been made, and such studies may reveal important clues for the solution of ash-flow problems.

Recognition and Definition of Units

General Discussion

The recognition and definition of ash-flow units pose one of the most difficult problems of pyroclastic flows, especially in deformed rocks. Perhaps the principal difficulty relates to the fact that the basic unit, one ash flow, is, in many instances, locally indistinguishable in multiple-flow cooling units. The problem is made more difficult because cooling units, or single ash-flows, may be separable in two dimensions but sometimes not in three dimensions. This is, of course, a common geological dilemma, but it has special significance for welded tuffs, because the unique properties of these rocks permit new approaches to the solution of old, as well as new, problems.

The splitting of units, and even of the basic unit, is commonly a function of the scale of mapping or of the degree of understanding one wishes to achieve. Thus, for reconnaissance mapping, a lithologic unit may be a heterogeneous volcanic field, whereas for detailed mapping a unit may be a texturally distinctive zone of one welded ash flow. The following discussion may appear to be needlessly complicated for many small ash-flow sheets and for some larger ones; for the great caldera-forming eruptions, however, the discussion is probably an oversimplification.

Flow Units

The usual concept of a flow unit, stemming as it does from our knowledge of historic

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it seems incredible that a
homogeneous flow unit

ardente eruptions, is restricted because of the small size of these deposits and the fact that they are confined to valleys. The flow unit of avalanche is generally considered the product of one nuée ardente, and at Pelée, for example, successive nuées ardentes were confined to the avalanche valley because they were erupted from the dome through a breach or notch in the crater rim. The resulting deposit in the valley inevitably is a stack of thin layers or flows, separated from each other by lava accumulations, fine ash, materials reworked by wind or water, or minor erosional unconformities. The nature of these partings may change from place to place between the same flow units, and locally a parting may not be readily detectable.

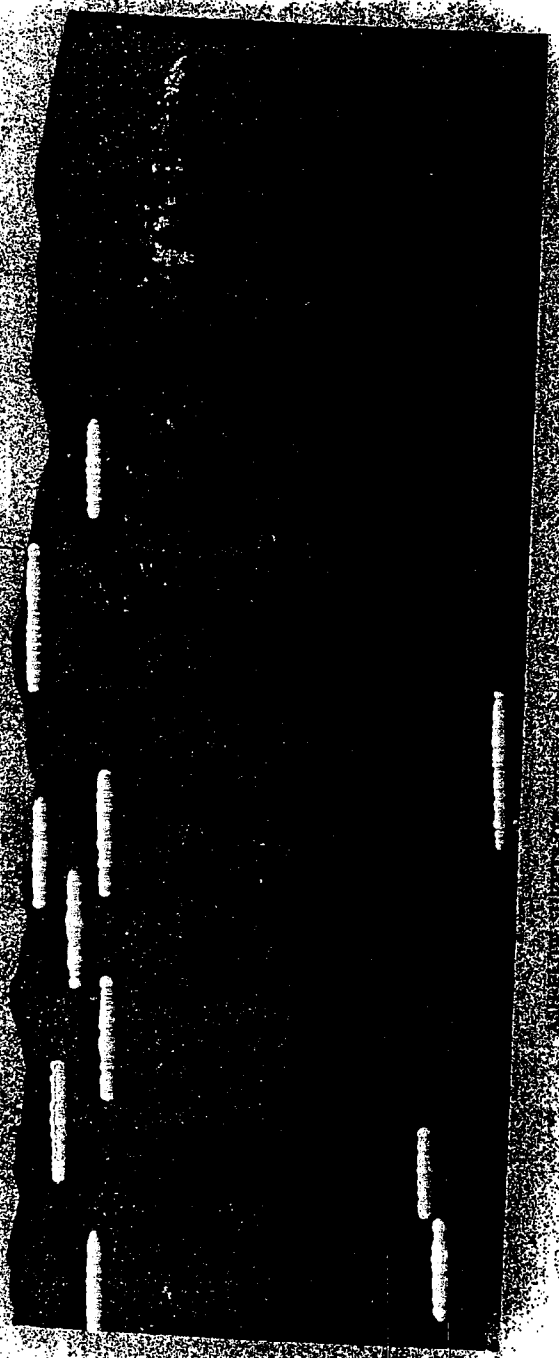
At Soufrière, because of the open crater, the distribution of the flows or avalanches was controlled largely by topography below the crater, and the materials poured down several valleys. Each of these valleys now contains a valley flow (presumably one from the May 7, 1902 eruption) which is a unit in itself, but all the valley flows are the product of a single eruption (except possibly minor material from the May 9 and 18 eruption).

Let us imagine a series of successive eruptions from a volcano in an environment similar to Soufrière. The first eruption may produce a group of independent valley flows. A second eruption produces an additional flow in each valley, but some of the flows may coalesce at the mouths of the valleys. As the surrounding ridges and valleys are buried by materials from successive eruptions and the terrain is leveled, the flows are no longer valley units but become successively larger, complexly lobate units. Finally they may become single sheet flow units continuous through 360° around the crater. This model assumes approximately uniform radial distribution from the crater. We may conceive of an eruption giving rise to a radially distributed single flow of petrographic homogeneity around small sources of the single-vent composite cone type. From larger source areas and from multiple vents such as those that culminate in large calderas in volcano-tectonic depressions, the pattern may progress with increase in dimensions and diversity of the source area to large and small overlapping and coalescing lobate sheet flows emitted radially in favorable sectors relative to their principal source vents. We should perhaps keep an open mind on the subject. It seems incredible that a single lithologically homogeneous flow unit could be formed from multiple vents, or even one great fissure, to cover an area the size of, for example, the Toba field (2000 square miles). Such units probably represent something more complex than a single flow even though random sampling indicates homogeneity. On the other hand, because of the probability of the intermingling of materials from multiple vents, or continuous evolution of great volumes of material from one or more vents, our concept of a flow unit must embrace compound flows that could conceivably show nearly all possible variations seen in welded tuffs, except incompatible chemical compositions.

No description of a single flow unit in its remaining or exposed entirety has yet been published, and it is doubtful whether geologists will undertake such a task in the near future. It will thus be a long time before we penetrate the intricate maze of the large ash-flow sheets and understand their history and the history of their source areas.

Our immediate concern with the flow unit is in one- and two-dimensional vertical sections where it must be defined as the thinnest recognizable virtually nonsorted layer. Its thickness may range from inches to hundreds of feet, and it may be separated from other flows by partings of diverse characteristics (Smith, in press). The visual recognition of partings, and hence flow units, may be very difficult and locally impossible in some welded tuff sheets. Some work suggests that the magnetic properties of individual flows may be useful in distinguishing them (Hatherton, 1954a; 1954b).

The writer thinks that some of these flow units as seen in two dimensions are actually subflows that originated within the main flow itself, rather than at a common point of origin in the vicinity of the source. These subflows may result from the lateral overlapping of lobes on an irregular front or possibly by vertical overriding due to volume surges or deposition on an irregular surface. These are conjectural concepts, but the overlapping of lobes around topographic prominences can cause the appearance of two flows in vertical sections downslope from the prominence, whereas there is only one upslope from it. Whatever their origin, such units represent a physically distinct and tabular flowage mass, and we have little choice but to call them flows until detailed mapping proves otherwise.



Cooling Units

In deposits of welded ash flows the single ash flow is commonly subordinate to a unit that consists of more than one flow (Pls. 1–2). The flows, however, have been emplaced in close enough succession so that they cooled virtually simultaneously, or in continuum over an extended period of time.

These multiple-flow units may show zonal patterns of welding and crystallization indistinguishable from the pattern shown by single ash flows having approximately the same temperature and thickness characteristics. It is therefore commonly more practicable and less ambiguous to think of any zoned unit as a cooling unit: *simple* if it exhibits the zonation of a single flow unit, or *compound* if the zonal pattern deviates from that expectable in a single flow.

Because of the common difficulty of recognizing flow units within densely welded cooling units, probably many of the so-called single flows are really multiple-flow cooling units. An excellent example of this problem is shown by the "ignimbrite" sheet at Maraetai 5, New Zealand. Marshall (1935, p. 347) writes of this "... no discontinuity could be seen in it of such a nature as to suggest that there was more than one period of deposition." R. Bailey (Oral communication), accompanied by J. Healy, has re-examined this sheet and has observed discontinuities that show that at least three flow units are represented. Hatherton (1954b, p. 427) distinguished three "sheets" by visual examination, whereas his measurements of remanent magnetism suggested five probable "sheets." A similar situation may exist in the Motutere section described by Marshall (1935, p. 351), as is indicated by reversals within his measured density sequence (Fig. 5).

Fenner (1923, p. 29–31 and 1948, p. 885), Gilbert (1938, p. 1836), Williams (1942, p. 82), Westerveld (1942, p. 204), and others recognized this problem, but details are lacking, especially for the more densely welded and crystallized sheets where distinctions are more obscure. Many, and perhaps most, welded tuff sheets should be re-examined with this thought in mind.

Composite Sheets

It can be demonstrated that all degrees of welding can exist at the contacts between flow units within compound cooling units. The parting between two flow units may at one place occur in densely welded tuff, whereas elsewhere it may occur in nonwelded tuff. The specific character of these contacts in any given place is related to the time interval between flows, the emplacement temperatures and thicknesses of the flows, and the number of flows that constitute the cooling unit. Some combinations of these variables will cause the formation of units that will show zonations in vertical sections ranging from the patterns of simple cooling, through degrees of compound cooling, to separate cooling units—separate, that is, in so far as we are able to detect continuous cooling in a vertical section. In complex fields of long-continuing eruptions we may expect that single cooling units in one area will grade into separate cooling units elsewhere. These may be separated by erosional disconformities.

The aggregate of cooling units joined by welding or crystallization in some areas, but grading laterally into two or more separate cooling units, is called a composite sheet (Smith, in press). Because it has not been documented by mapping, although supported by inspection in a few localities and inferred in

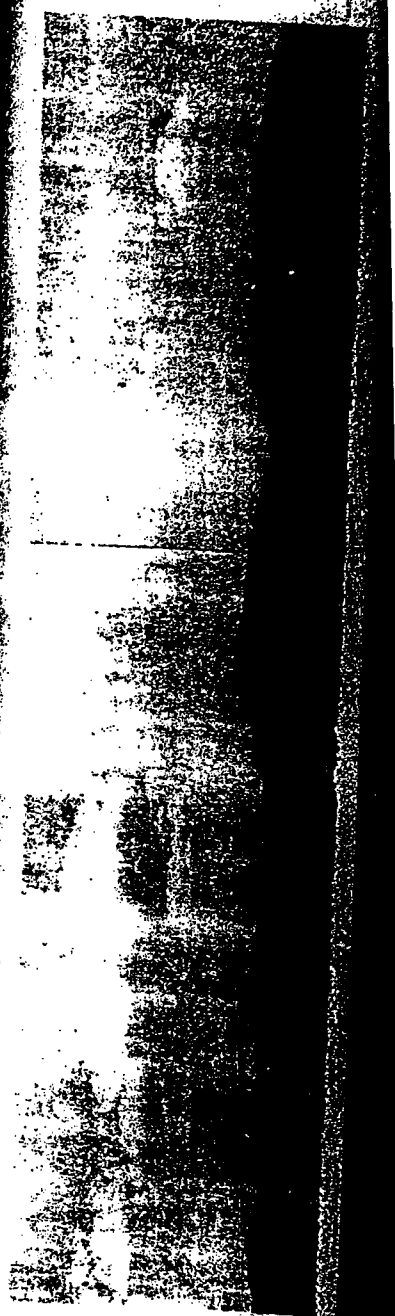


PLATE 1.—ASH-FLOW SHEETS ON THE PAJARITO PLATEAU NEAR LOS ALAMOS, NEW MEXICO

Two members, separated by an erosional disconformity and air-fall beds, make up the Bandelier rhyolite tuff in the photograph. The lower member is a nonwelded and vitric ash-flow unit that underlies the lower, tree-covered slopes of the mesas. The air-fall tuff and disconformity are visible at the far left, at the base of the overlying cliff-forming member. The upper member is a multiple-flow cooling unit whose partings are clearly emphasized by weathering. It is mildly welded and crystalline (vapor-phase zone) from the top of the mesas down to the middle of the lower dark band about midway up the exposed sections. The lower half of this band is a nonwelded, reddish, vitric zone. The degree of welding increases toward the mountains beyond which lies the source area. The partings between flow units become more obscure and locally invisible with increase in degree of welding. Photograph by R. A. Bailey.

FIGURE 1

FIGURE 2

VARIABLE WELDING IN THE BANDELIER RHYOLITE TUFF

others, the unit is referred to as hypothetical until it can be accurately mapped. The existence of such a sheet seems inevitable, and it may eventually prove to be the most significant unit in terms of the eruptive and structural history of the source area, especially in deposits of large volume.

Additional problems of correlation may arise in ash-flow fields that are separated into sectors by topographic barriers. Here the composite unit in one sector could conceivably have single-flow or separate cooling-unit counterparts in other sectors.

Ash-Flow Fields

An ash-flow field as here defined is the aggregate deposit of ash flows that can be related as a unit, or as a group of integral parts, to a specific source or source area. It may consist of any one or all of the other units either in single or multiple forms. The source is any simple volcanic vent such as a dome, crater, or small fissure, whereas source area refers to calderas, volcano-tectonic grabens, or other complex vent systems. Obviously such a flexible term cannot have meaningful genetic connotations, and it is used here only in a descriptive sense to provide some measure of order to an otherwise heterogeneous complex of volcanic rock deposits. One can envision subfields, superfields, multiple fields, and so forth, but such subdivisions call for data not available at present.

Ash-flow fields, in their entirety or in part, include Toba (Westerveld, 1947), New Zealand (Grange, 1935), Aso (Matumoto, 1943; Williams, 1941a), Chiricahua (Enlows, 1955), San Juan (Larsen and Cross, 1956; Ratte and Steven, 1959), Valles (Ross and Smith, in press), and many others, are stacks of cooling units or composite sheets with varying amounts of interbedded ash.

It is inferred that the greater the number of cooling units, and the greater the differences among them, the longer and more complex has been the eruptive history in the source areas.

Magnitude of the Deposits

Distance Traveled

The maximum distance an ash flow can travel from its source is not known. It may be of the order of 100 miles, although such a distance would be unusual in the light of existing data. Theoretically, temperature and gas content, hence the gas-emitting properties of an ash flow, appear to be the most significant variables influencing distance traveled. When actual distances traveled by specific ash flows are compared, however, gradient, topography, and especially volume appear to have exerted a greater control.

Figure 2 shows some maximum distances from known or inferred probable source areas. The most reliable figures for the greater distances are probably those given by Williams (1942, p. 79) for the "pumice flow" that can be traced down the Rogue River valley for 35 to 40 miles, and by Matumoto (1943, p. 4) who states that the farthest outcrop of the "Aso lava" is 100 km from the center of Aso caldera. The Nomlaki tuff of the northern Sacramento Valley, California (Anderson and Russell, 1939), may have traveled 50–65 miles or more from an unknown source on the eastern

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PLATE 2.—VARIABLE WELDING IN THE BANDELIER RHYOLITE TUFF

FIGURE 1.—Three members of the Bandelier tuff along New Mexico Highway 4 near Totavi, New Mexico. Above a basaltic lava flow at the man's feet is a basal member of air-fall beds of lump pumice and ash of variable thickness. The nonwelded and vitric middle member (lower member in Pl. 1) underlies the treed slope. The upper member is the multiple-flow cooling unit of Plate 1, crystalline and mildly welded throughout. Cooling with a probable increase in emplacement temperature toward the top. Photograph by R. A. Bailey.

FIGURE 2.—North wall of Frijoles Canyon, Bandelier National Monument, New Mexico. Upper half of photograph equals upper member of Figure 1 of this plate. The darker layers indicate higher degrees of welding than the lighter. The lower light-colored cliffs are formed in nonwelded materials and are pocked with wind-eroded holes. Prehistoric Pueblo Indian ruins at their base are a feature of nonwelded parts of the Bandelier ash flows in the Jemez Mountains. Photograph by George A. Grant, courtesy of the National Park Service.

side of the valley to the foothills of the western side. On the western side of the valley the tuff sheet has an outcrop area of more than 40 miles in a north-south direction.

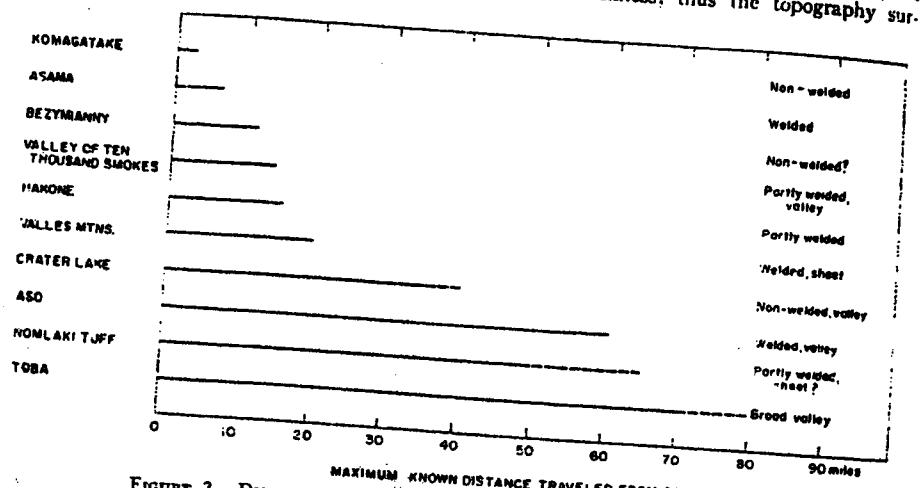

FIGURE 2.—DISTANCE TRAVELED BY ASH FLOWS FROM THEIR SOURCE

Komagatake (Kuno, 1941, p. 146); Asama (Aramaki, 1956, p. 209); Bezymianny (Gorshkov, 1959, p. 94); Valley of Ten Thousand Smokes (Griggs, 1922, p. 253); Hakone (Kuno, 1950, p. 272); Valles Mountains (Ross and Smith, in press); Crater Lake (Williams, 1942, p. 79); Aso (Matumoto, 1943, p. 4); Nomlaki Tuff (Anderson and Russell, 1939, map); Toba (Westerveld, 1947, map).

The distance of 80 miles shown for the Toba tuff represents the most distant outcrop of tuff, shown on Westerveld's (1947) map, measured from the northwest rim of the Toba depression down the L. Biang and S. Wampoa valleys. This is tentative, however, because the most distant outcrop may represent fall deposit rather than flow.

Many deposits of ash flows are continuous for more than 50 miles, but in the absence of a known source area all such distances probably represent only a partial dimension of a large sheet. Mackin (1960, p. 95) and Cook (1958, p. 1548) have mentioned single welded-tuff units that extend for more than 100 miles in southwestern Utah and southeastern Nevada. If this represents distance from a source it is a prodigious figure, but if it represents diameter or long dimension of a single sheet it is large but not excessive when we consider, for example, the Toba tuff which is a continuous map unit for more than 150 miles. Admittedly this may not be a fair comparison, because the individual units of the Toba tuff have not been distinguished. However, the comparison does emphasize the large size of some welded-tuff deposits.

Area

The area covered by ash-flow fields is, of course, a function of the volume of the deposit and its thickness; thus the topography surrounding a source area influences the thickness of the tuff, its area, and its symmetry. Figures generally quoted for area and volume are for *pyroclastic fields* which may or may not (ordinarily not) consist of one ash flow. Usually the eruptive history of any field is so complex that detailed mapping has not been done and the number and kind of units are not known.

It is therefore easy to overlook the fact that when the magnitudes of such ash-flow fields as Crater Lake and Aso are compared, they are not geologically equivalent. The Crater Lake deposits (Williams, 1942) appear to represent one catastrophic eruptive period and thus one unit, which, notwithstanding the fact that it probably consists of many ash flows, appears to have been a unit of cooling. The Aso deposits, on the other hand, comprise at least three if not five or six major cooling units and thus represent several periods of eruption separated by at least one marked disconformity (Williams, 1941a; R. A. Bailey, oral communication). Conditions similar to or more complex than those at Aso are common in a great many ash-flow fields surrounding calderas. They show the complexity of formation of these fields and associated calderas.

The known areas and volumes of specific ash-flow fields have been partially tabulated by several writers (Westerveld, 1942, 1952; Weyl, 1958; Rittmann, 1958, p. 335). Some of these areas and volumes are incorporated in Figure 3. The most interesting and geologically important ash-flow fields cover several hundreds to thousands of square miles. Some of them contain sheets of densely welded tuff throughout their entire known area. Few, if any, are known in great detail, and many years of work will be necessary to determine their volume, source, number of eruptive cycles, and tectonic relationships.

The field most often cited as the world's largest is that of the Lake Toba region, Sumatra. The North Island, New Zealand. Here again comparison is difficult because of basic differences in the characteristics of each field. Though these two are probably better known than others, they are as yet not really well defined. Toba as deduced from the writings of Bemmelen (1949) and Westerveld (1951, 1952) appears to be enormous but not fully complex when compared to New Zealand. The ash-flow sheets seem to have originated within a relatively short period of time over the area now occupied by the giant Toba volcano-tectonic depression. The New Zealand field, on the other hand, seems to be made up of ash-flow sheets from numerous sites, erupted at different times, and, in time, as a consequence, the eruptive history of the Taupo-Rotorua graben in North Island seems far more complex than that of the Toba depression. Both large fields are so little known that we can only record their existence.

YELLOWSTONE ASH-FLOW FIELD: Boyd (1957, p. 1, thesis, Harvard, Cambr.) has recently estimated that Yellowstone National Park contains 600 square miles of welded tuff exposed within the park; added to the probable extent and extension of the field this gives a total area of 2000 square miles. Addition of an equal area presumed to underlie the plateau rhyolite flows and the Snake basalts gives a total of 4000 square miles. Within the park the volume ranges from 400 to 1000 feet. With 700 feet as an average original thickness and 2000 square miles as probable areal extent, he calculated that the volume of welded tuff would be on the order of 400 cubic miles. This suggests that it was all emplaced in a single and sequence of eruptions.

LAKHANDA MOUNTAINS ASH-FLOW FIELD: One of the largest ash-flow fields known is that of the Lakhanda Mountains, Montana, volcanic field of Late Cretaceous age which surrounds and was intruded by the Boulder Batholith. This field appears to consist of several thick and extensive welded-tuff sheets which occupy a minimum area of 5000 square miles and have a minimum volume of 500 cubic miles, but which may have an area as great as 10,000 square miles and a maximum volume of 1000 cubic miles (Klepper and Smedes, 1959, p. 1041; and oral communication).

SAN JUAN MOUNTAINS ASH-FLOW FIELD: One of the most spectacular and complex ash-flow fields in the world is associated with the San Juan Mountains volcanic pile in Colorado and northern New Mexico. Of specific interest are three of the upper members of the Potosi series—the Treasure Mountain, the Silverton, and the Picayune. Larsen and Cross estimate total volume for these as 2330 cubic miles. From the work of geologists of the U. S. Geological Survey, including Burbank, Larsen, Luedke, Olson, Ratte, Ross, Steven, and others, and evaluation of field data over a period of 15 years by R. A. Bailey and the writer, it can be said that most, if not all, of the three members are silicic pyroclastic rocks, in large part welded tuff. The area covers approximately 12,000 square miles. At present only one source area, the Creede caldera (Steven and Ratte, 1960; Ratte and Steven, 1960), is definitely known. Two other caldera, the Silverton and Lake City (Burbank, 1941; Burbank and Luedke, oral communication, 1959), are seemingly related to the older rock series among which ash flows are also known. The field should be classed as a multiple-source field; other source areas remain to be found and related to specific salients of the field.

SUDBURY BASIN. On the basis of recent work in the Sudbury Basin, Ontario, Canada, Thompson (1957, p. 43) and Williams (1957, p. 69, 70) have postulated that the Sudbury "lopolith" is really a volcano-tectonic depression surrounded by a ring of eruptive centers and that the subsided basin contains no less than 300 cubic miles of "glowing-avalanche" deposits. Deposits about a mile thick are believed to occupy about 300 square miles within the basin.

BASIN AND RANGE ASH-FLOW FIELDS: Another tremendous, and probably very complex, ash-flow field occupies an area of more than 10,000 square miles in southwestern New Mexico. It comprises large parts of the Datil, Mogollon, Black, Tularosa, and other mountains and probably has a volume equal to or greater than

the San Juan field. This field is a small part of the vast volcanic system of Tertiary age of the Basin and Range province of western United States and Mexico.

Welded tuffs in the Basin and Range province have long been known, although Ross (1953; 1955, p. 430–432) seems to have been the first to make a clear statement in the literature. Recently Williams (1957, p. 64) has stated that not less than 50,000 square miles of southern Nevada and southwestern Utah was buried to a maximum depth of about 8000 feet by "fissure-erupted glowing avalanches" during late Tertiary time. Mackin (1960, p. 83) has estimated the volume of silicic volcanic rocks in the Great Basin to be about 50,000 cubic miles, and this is probably conservative.

Thickness

Many figures have been published for thicknesses of "welded-tuff sheets," "ignimbrite sheets," "glowing-avalanche deposits," "tuff flows," and related rocks. What these thicknesses mean in terms of the units defined in this paper is problematical. For many general problems the lack of detail is not serious, but it is critical to many genetic problems if units of equal rank must be compared. Perhaps most published figures are for aggregate tuff deposit or deposits, and figures for "a welded-tuff sheet" or "an avalanche deposit," or "one ignimbrite" may commonly represent multiple-flow cooling units.

Marshall (1935, p. 328) found that the New Zealand "ignimbrites" range from 60 to 500 feet in thickness but stated that many are less than 100 feet thick. Some are probably single-flow units, but we now know that others are multiple-flow cooling units. Jenks and Goldich (1956, p. 162) state that locally the "white-tuff flows" are 160 feet thick, whereas three successive tuff flows composed of salmon sillar, with very little interbedded material, aggregate 500 feet.

Enlows (1955, p. 1221) gives figures ranging from 2½ to 880 feet for the seven or eight "members" of the Rhyolite Canyon formation, which he considers welded tuff. He infers (p. 1219) that each layer or "member" is the product of one "nuée ardente" or "hot-ash" eruption. Member No. 6 contains 700 feet of densely welded tuff. Mansfield and Ross (1935, p. 312) found that their Idaho welded tuff ranges in thickness from 20 to 50 or more feet.

Individual pyroclastic flows evidently range from a few inches to hundreds of feet in thickness. Their individual character is probably determined primarily by their volume and by topography, although we might expect that, if volume and topography were the same, the hotter, finer-grained flows would be thinner than the colder, coarser-grained ones, although this difference might be influenced by gas content. Other variables might be considered, but at any rate we must expect that small-volume, short-burst eruptions from "Pelean" domes will result in thinner flows than will larger-volume, continuous-evolution-type eruptions from craters or fissures. Nevertheless the latter type may also result in thin flow units. Most multiple-flow cooling units probably have a similar range in thickness but have a higher average thickness than do single flow units. Exceptionally thick cooling units are known.

The thickest welded-tuff sheet that the writer would interpret as a cooling unit is the Superior dacite in the Globe-Miami-Superior area, Arizona. This welded-tuff sheet was kindly shown to him in 1956 by N. Peterson and in 1957 by D. Peterson, both of whom have studied parts of it in some detail. The Superior dacite was originally described by Ransome (1903) as a lava flow more than 1000 feet thick, and again by N. Peterson, Gilbert, and Quick (1951), who discuss the possibility of its pyroclastic origin. D. Peterson (1959, p. 1740) presents the evidence for a pyroclastic origin and suggests that the sheet, which covers at least 400 square miles and is locally as much as 1300 feet thick, "was deposited by a single huge pyroclastic eruption." The precollapsed thickness of this sheet was probably well over 2000 feet. Publication of the details about this most interesting welded-tuff sheet will add greatly to our understanding of the problems.

Thicker cooling units may exist in the San Juan Mountains of Colorado. Those currently being studied by Steven and Ratte (1959, p. 1788) in and around the Creede caldera are of special interest. Ratte and Steven (1959, p. 1785) report two major stages of ash-flow deposition: (1) a precaldera rhyolitic stage forming deposits more than 3500 feet in thickness and ranging from densely welded tuff "resembling fluidal rhyolite in the lower part to essentially nonwelded pumice breccia at the top", and (2) a caldera-subsidence stage presumably culminating in more than 4000 feet of quartz latitic welded-ash flows that are now exposed in the caldera core. Other lesser ash-flow, pyroclastic, and lava-flow units occur within the volcanic edifice.

Stacks of cooling units in the Basin and

Range province in
maximum of 8000 feet
Such thicknesses pr
lapping fields which,
thicker.

Volcanic Vents

The most critical
especially the large
concerns the location
the source areas.

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[illegible] Volcanic Vents and Source Areas

[illegible] most critical problem of ash flows, [illegible]cially the large-volume sheet deposits, [illegible]erns the location and characteristics of [illegible] source areas.

Domes

[illegible]th few exceptions, historic nuées ardentes [illegible] been erupted from volcanic domes and [illegible] produced deposits of small volume and [illegible]stricted distribution. None of the deposits [illegible] domes is known to have formed welded [illegible] although incipient welding in some of [illegible] deposits may have been overlooked. Even [illegible]ough future studies show that some eruptions [illegible] domes resulted in the formation of welded [illegible] this should in no way obscure the fact that [illegible] deposits will be rare, relative to welded [illegible] of other origins.

[illegible] best known examples of nuée-ardente [illegible]ptions from domes are the 1902 and 1929–[illegible]32 eruptions of Pelée, Martinique, and the [illegible]odic eruptions from Merapi, Central Java. [illegible] recent eruptions were Mt. Lamington, [illegible] Guinea (Taylor, 1954; 1956), Hibok-[illegible]bok, Philippines (Macdonald and Alcaraz, [illegible]56), and Bezymianny, Kamchatka (Gorsh-[illegible] 1959).

Craters

[illegible] classical example of a nuée-ardente [illegible]ption from an open crater is the 1902 erup-[illegible] of Soufrière, St. Vincent. The resulting [illegible]-flow deposits were seemingly unconsoli-[illegible]ted. Incipient welding was probably pre-[illegible]ded, not because of too low a temperature, [illegible] because of the high-crystal, low-glass [illegible]tent and inadequate thickness.

[illegible] Welded tuffs have been produced by historic [illegible]ptions from open craters, although the few [illegible]mples are of types far removed from rocks [illegible]mally called welded tuffs. Aramaki (1956) [illegible] described the "Agatsuma nuée ardente" [illegible] one of the products of the 1783 activity of [illegible]ma volcano. One lobe of this flow reached [illegible] km from the crater, its total area is esti-[illegible]ted at 18.5 km, and its volume (assuming an average thickness of 5 m) is approximately 0.1 km³. The thickness ranges from more than 10 m in the central part to less than 4 m at the edges.

Fissures

Small central vents can undoubtedly produce welded tuffs, but most recent writers believe that the large-volume ash-flow sheets (tens of cubic miles) have been erupted from fissures (Williams, 1957, p. 64; Westerveld, 1952, p. 564–568; van Bemmelen, 1949, p. 202; Ross and Smith, in press). Some writers have postulated, in the absence of positive evidence for fissures, that the fissure vents for these large-volume deposits are buried beneath the ash-flow sheets (Cotton, 1952, p. 211; Weyl, 1954, p. 25).

No evidence unequivocally supporting such a concept has been published. Several writers have found fissure dikes which they thought were feeders, but none has proved it. As indicated above, the writer is speaking of deposits with a volume in excess of several cubic miles. This would exclude the deposits of the Valley of Ten Thousand Smokes deposit which Williams, Curtis, and Juhle (1956, p. 129) now believe to have been erupted from fissures at the head of the Valley as well as from the vent now occupied by Novarupta. Fenner (1923) held much the same view, although he also suggested fissures on the Valley floor as a supplementing source. As pointed out by MacGregor (1952) Fenner has often been misquoted on this point.

The New Zealand ignimbrites are often cited as fissure-erupted materials, and the "positive" evidence seems to center around an "ignimbrite dike" which outcrops at Ongarue, and which is pictured by Cotton (1952, p. 210, Fig. 102). The writer has been skeptical of the "feeder dike" interpretation for many years and was interested to learn from Roy A. Bailey (oral communication, 1957) who has examined the outcrop in the field, that there is indeed some doubt as to the intrusive origin of the "dike". It shows a horizontal planar eutaxitic foliation just like that seen in the surrounding ignimbrite rather than the vertical lineation expected in a dike. Bailey suggests that the horizontal jointing may be related to an abnormal cooling surface such as might be found if an ash-flow filled a narrow gorge. Detailed study is needed. Aside from this one doubtful locality it would appear that no occurrence is known where pyroclastic dikes actually project into ash-flow sheets where it can be shown or rea-

sonably inferred that the dikes were actually feeders for the large-volume deposits.

The evidence for fissure feeders seems established for at least part of the Valley of Ten Thousand Smokes deposit (Williams, 1954) and for an extremely interesting occurrence in the John Day formation of Oligocene age in Oregon, kindly shown the writer by A. C. Waters. In the latter area a dike several miles long appears to change from fluidal rhyolite in its deepest exposed part to fluidal-fragmental welded tuff near the surface and merge with a densely welded tuff sheet on the surface.

Other areas where fissure feeders are suspected include the Pilomasin basin, Sumatra (van Bemmelen, 1949, p. 681), Macdoel quadrangle, California (Williams, 1949, p. 32), Sudbury, Ontario (Williams, 1957, p. 64), Independence Pass, Colorado (Burbank and Goddard, 1935), and Black Range, New Mexico (Kuellmer, 1954).

The negative evidence favoring fissure vents for the large-volume ash flow sheets is inconclusive but nevertheless more suggestive:

(1) Specific central vents as source vents seem as rare as fissures

(2) Apparent absence of volcanic cones in association, in many areas, with ash-flow sheets

(3) Linear arrangement, in some areas, of post-ash flow vents and intrusive rocks

(4) Post-ash flow collapse along arcuate fractures or other linear zones of weakness producing calderas and volcano-tectonic depressions

It is significant that nearly all ash-flow fields with a volume of more than a few cubic miles and that have been related unequivocally to source areas are associated with calderas or other depressions of subsidence. The specific vents of emission of the ash flows no longer exist at the surface; they were destroyed by the collapse after or during eruption. Those vents that were not destroyed or that may be present in the collapsed blocks are probably modified by structural readjustments, post-collapse volcanism, or intrusion, and are no longer recognizable. In deeply dissected volcanic and volcanic-plutonic structures conduits may have been obliterated by ring dikes, stocks, or other intrusive bodies.

Calderas and Volcano-Tectonic Depressions

Subsidence related to igneous activity has long been recognized, but van Bemmelen (1930) is probably to be credited with the theory of catastrophic engulfment of volcanic edifices after the eruption and draining of magma chambers of large volumes of pyroclastic material. Williams (1941a) and others have reiterated and amplified this view, calling attention to the fact that many of the pyroclastic deposits surrounding such collapse structures are of "nuée-ardente" origin, and that many of these deposits contain welded tuffs.

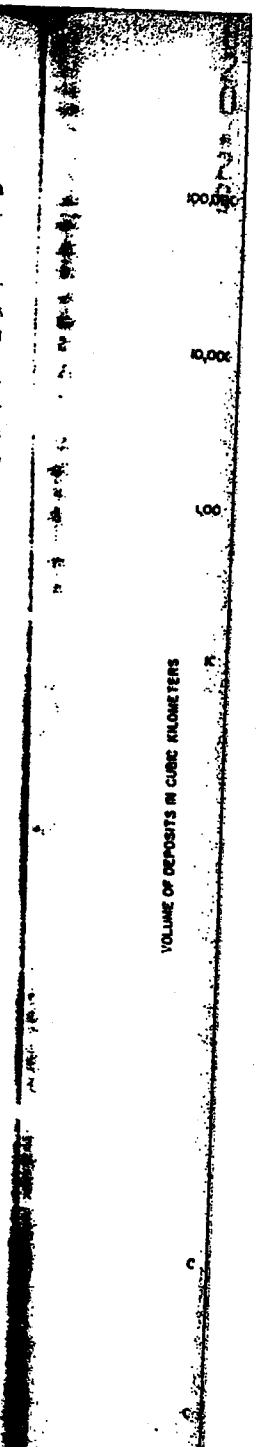
Specifically, when we find welded tuffs or other ash-flow deposits, where cooling units or composite sheets can be shown to have volumes of a few to many cubic miles, we may expect to find subsidence structures in the source areas. The existing positive evidence for young (Pleistocene and Recent) deposits supports this view. The characteristics of these structures may vary, but probably caldera-type structures predominate.

Figure 3 shows volumes for a selection of pyroclastic flow deposits. The logarithmic method of plotting gives undue weight to differences in the smaller deposits and suppresses more significant differences in the larger deposits, but it also allows a grouping of deposits on a small-scale plot which has geologic meaning.

This breakdown by volume is not an attempt at classification in the sense of Aramaki's (1957, p. 21–31) important three-fold classification of pyroclastic flows, but rather an attempt to generalize the interrelationship of volume of deposits with types of source areas. It is especially designed to show that where source areas are known, and well studied, for deposits of large volume these areas are sites of volcanic or volcano-tectonic subsidence, a fact which should be of critical importance, especially to students of older rocks.

The figures for volumes shown in Figure 3 are the best available. Unfortunately it is problematical if many can be compared as equivalent entities. The figures represent units of all rank between single-flow units and complex pyroclastic fields and are not converted to equivalent porosities. However, if we take cooling units or composite sheets as here defined as the units to be compared, it is doubtful if subdivision of the larger fields or more accurate estimates of volumes of the deposits will change the figures more than one order of magnitude.

The data suggest that the maximum volume for deposits erupted from volcanic domes, and hence Pelean-type deposits, strictly speaking, is in the fourth order of Figure 3, or somewhere between 1 and 10 km³. Most of these deposits have a volume less than 1 km³. None is known to contain welded tuffs. The term "Pelean" should probably be restricted to deposits of



The volumes, in km³, 0.01 to 10,000 km³.

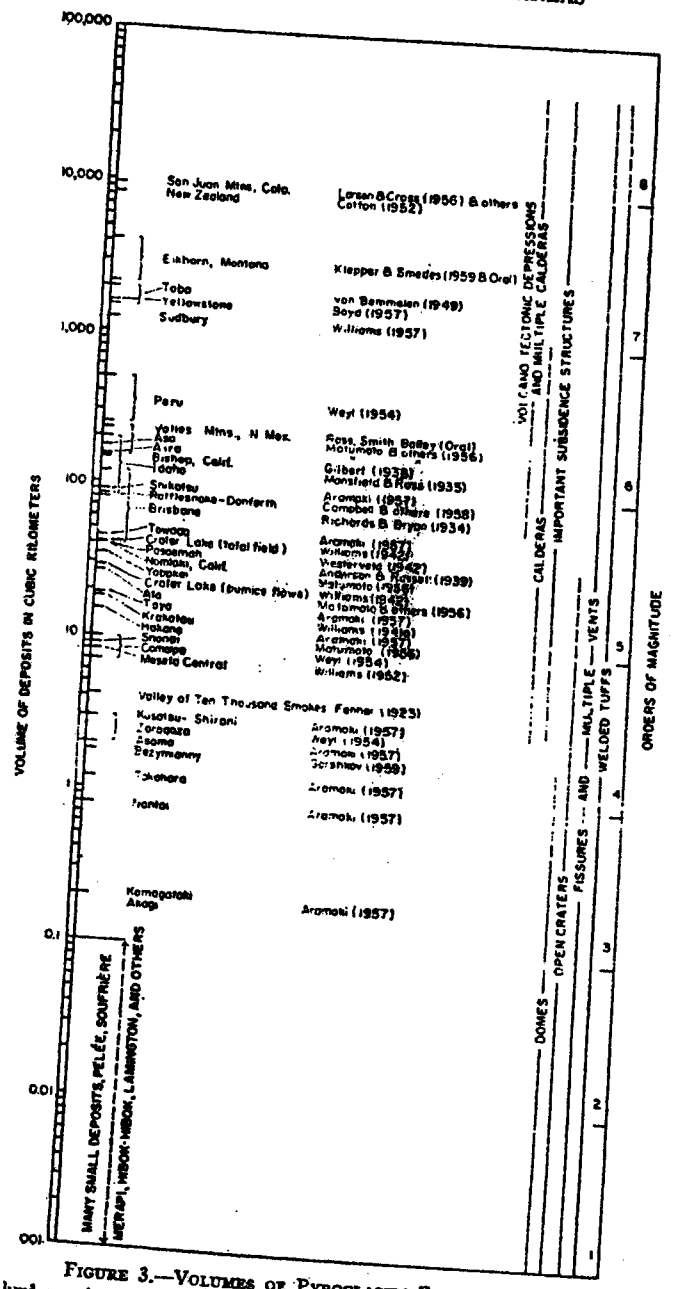


FIGURE 3.—VOLUMES OF PYROCLASTIC-FLOW FIELDS

The volumes, in km³, are plotted on five-cycle logarithmic paper and span seven orders of magnitude from 0.01 to 10,000 km³. The data show a correlation with vents and source areas.

these low orders of magnitude erupted from domes, irrespective of whether or not their emplacement mechanics are also applicable to other deposits.

The maximum probable volume from single open craters may also be in the fourth order, although the fifth cannot be ruled out. The overlapping of caldera formation obscures the nature of vents in most examples described. Deposits found around calderas which have formed in single giant cones may have been erupted from the central crater, or they may have been erupted along the boundary fractures of the subsided block or from fissure systems in the block.

All known large calderas (sixth order of Fig. 3) such as Aso and Valles, and some smaller ones such as Toya and others, are not related to single cones but rather were formed by subsidence of parts of volcanic plateaus, groups of cones, or broad volcanic shields. It is difficult to imagine single vents or even multiple vents, other than those associated with fracture (fissure) systems related to the collapse itself. The same is presumably true of many subsidence structures, both smaller and larger than those calderas associated with sixth order ash-flow deposits, which were guided by pre-existing or active tectonic trend lines and are called volcano-tectonic depressions.

Ash-flow deposits of orders 5, 6, and 7 seemingly either are associated with collapse structures or their source areas are unknown. The writer has been unable to find a well-authenticated exception in the literature. Deposits from large composite cones such as Mt. Mazama (Crater Lake) evidently reach their maximum volume in order 5. They surely do not exceed 100 km^3, and probably most are smaller than 50 km^3.

Of the ash-flow deposits grouped in order 6, the sources of the Brisbane tuff, the Idaho "welded tuff", and the Peruvian "sillars" are unknown, and the volume estimates are very tentative. Gilbert (1938, p. 1859–1860) suggested a possible relation between the extrusion of the Bishop tuff and faulting in Long Valley. The remaining three fields—Aso, Aira, and Valles (order 6)—are genetically related to structures of the same names which have been called the world's largest known calderas. Each exceeds 12 miles in diameter.

The ash-flow fields of order 7 have been mentioned briefly in the section on Area. Thompson (1957) and Williams (1957) consider the Sudbury basin to be a volcano-tectonic depression; Boyd (1957, Ph.D. Thesis, Harvard Univ.) noted a "tectonic basin" in Yellowstone Park and suggested a caldera origin, but he was uncertain whether subsidence was consequent on the eruption of 400 cubic miles of welded tuff or associated with 200 cubic miles of rhyolite flows that now nearly fill the basin. Toba (van Bemmelen, 1939) is the classical, and one of the largest, volcano-tectonic depressions. It is only one of several along the Barisan Mountain Range in Sumatra. The source of the Elkhorn, Montana, ash-flow field is not known and may have been totally obscured by the intrusion of the Boulder batholith: Grange (1934; 1937), Williams (1941a), and others have considered the New Zealand "ignimbrites" related to Taupo-Rotorua graben which is considered to be volcano-tectonic in origin. Within the San Juan volcanic field three giant calderas are known, but only one is known to be directly associated with the ash-flow field discussed on an earlier page and plotted on Figure 3. The volume of the field seems incompatible with a single structure, and the field should probably be classified as a multiple-caldera field.

Within the tremendous ash-flow complex of southwestern New Mexico, mentioned earlier, lie the Plains of San Augustin, a grabenlike structure probably larger than the Toba depression. It is floored with Pleistocene sediments and volcanic ash. Griggs (1954, p. [illegible]) has suggested that this "prominent [illegible] depression" is a collapsed structure related to the eruption of the associated welded tuff. Griggs reports beds of welded tuff downfaulted to low elevations in the interior of the plains and rhyolite domes in the interior and at the margins. It may be significant that this structure lies very close to the junction of two major tectonic trends at the southeast margin of the Colorado Plateau; its long dimension lies athwart the directions of these trends.

The Deposits

Introductory Statement

As stated earlier, recognition of welded tuff still is a major problem, especially in older rocks, and in the absence of clear-cut geologic relations it is not always possible to distinguish welded tuffs from lava flows. Many writers have considered criteria for recognition of welded tuffs, notably Marshall (1935), Gilbert (1938), Weyl (1954), Enlows (1955), Ross and Smith (in press). No single criterion is in itself

infallible. The ultimate criteria are those that establish that the rock is or was composed of vitric, at least in part, pyroclastic materials, chiefly glass shards and pumiceous fragments, and that these have been deformed and welded while they were still hot. The writer has found that the most pertinent observations are usually made at or near the base of the unit in question. Here the transitions from nonwelded to densely welded and from glassy to crystalline rock are within a few feet, and the physical changes in the fragmented materials may be easily traced, in contrast to the more gradual changes in the upper part of the sheet. Even after some metamorphism, relict vitroclastic structure may still be present in what was formerly the densely welded glass zone. The base of a welded-tuff sheet does not show the basal breccia zone normally found in silicic lava flows.

Even more difficult than the distinction between some welded tuffs and lava flows is the distinction between nonwelded ash flows and tuffs of other origins. Voluminous pyroclastic fall materials, near source areas, as well as avalanches of loose accumulations of pyroclastic materials may be indistinguishable from true pyroclastic flows, although the origin of most such deposits is decipherable if they can be traced laterally.

Sorting Characteristics

Ash-flow deposits are generally nonsorted, as can be seen in any outcrops of nonwelded or poorly welded materials; fragments range in size from blocks to dust. The chief differences among deposits seem to be in the proportions of coarse to fine materials and in the relative proportions of crystals and glass. Before welding or crystallization, most ash-flow deposits are composed of (1) glass shards and glass dust, (2) pumice or scoria fragments and occasionally bombs, and (3) crystals; glass generally predominates over crystalline materials. Most contain some accidental lithic fragments.

The existing data do not indicate that major sorting is ever an important phenomenon of the flowage mechanism itself. Probably, however, heavy accidental inclusions, other than those locally derived, will decrease in size and amount from source to distal end of a given flow. The amount of fine-grained materials should probably also increase away from the source, especially in flows of low gas content.

Figure 4 shows cumulative grain-size curves for localities where size analyses are available. Although few in number, they are remarkably similar. The following localities are represented:

(1) The "Shirasu" deposits, South Kyushu, Japan (Taneda, 1954; 1957; Taneda, Miyachi, and Nishihara, 1957)

(2) Pumice deposits at Komoro on southwest foot of Asama volcano, Japan (Tsuya, Murai, and Hosoya, 1958)

(3) "Older pumice", Crater Lake (Moore, 1934)

(4) "Sand flow", Valley of Ten Thousand Smokes (Fenner, 1923)

(5) "Sillar" near Arequipa, Peru (Jenks and Goldich, 1956)

(6) Nonwelded portion of "ignimbrite", Arapuni, New Zealand (Marshall, 1935)

The "Shirasu" and the Komoro deposits are by far the best studied for their sorting. The "Shirasu" curves, Sh-35 and Sh-60, represent the highest and lowest median (size at 50 per cent) values of nine samples considered by Taneda and others to be representative of the bulk deposit. The Komoro curves, K-5 and K-8, also represent the highest and lowest median values of nine samples considered to be representative of the bulk deposit, and curve K-10 represents the fine-grained upper layer of the deposit.

The Crater Lake curves, C-34 and C-53, are the coarsest and finest of four samples but cannot be too closely compared with the others, because they do not include material larger than 64 mm in diameter. As a result their median particle sizes are larger, and their total contents of ash-size material are somewhat smaller than shown here.

The "sand-flow" and the "sillar" curves are not adequate representation of their respective deposits, but neither can they be much in error. The same may be said for the Arapuni, New Zealand, curves, which are both from the same "ignimbrite sheet", one from above and the other from below the welded zone.

The significant thing shown by these curves is the preponderance of ash and fine ash-size materials. In all the samples plotted 70 per cent of the material is smaller than 4 mm. The median sizes lie between 0.08 and 0.8 mm, or close to one order of magnitude. As mentioned above, at least some of the Crater Lake material will be generally coarser if the sizes above 64 mm were included.

The data, few as they are, are a surprisingly good representation of ash flows. The "Shirasu" is a deposit of large volume associated with the

"hai-ishi" (welded tuff) which surrounds the giant Aira caldera. The "older pumice" is a nonwelded deposit associated with the formation of Crater Lake caldera in a large composite andesitic volcano; the Komoro deposit is a small-volume nonwelded "pumice flow" presumably from the summit crater of Asama volcano, an andesite cone. The "sand flow" of the Valley of Ten Thousand Smokes, a small-volume deposit erupted from fissures and perhaps a crater, is at least partly welded and is partly crystalline. The Peruvian "sillars" are from a large-volume deposit of unknown origin and consist of nonwelded, mildly welded, and crystalline facies. The Arapuni samples represent a finer-grained type of the fissure-erupted "ignimbrites" which form the vast tuff deposits of the North Island of New Zealand.

The writer offers with considerable confidence the opinion that *most* welded tuffs have been derived from ash flows having sorting characteristics within the range of the cumulative curves of Figure 4. Some, nevertheless, will contain a higher proportion of coarse blocks of pumice or scoria, and a few such as the welded tuffs from Idaho, studied by Mansfield and Ross (1935), and the Walcott tuff (Stearns and Isotoff, 1956) are probably finer-grained.

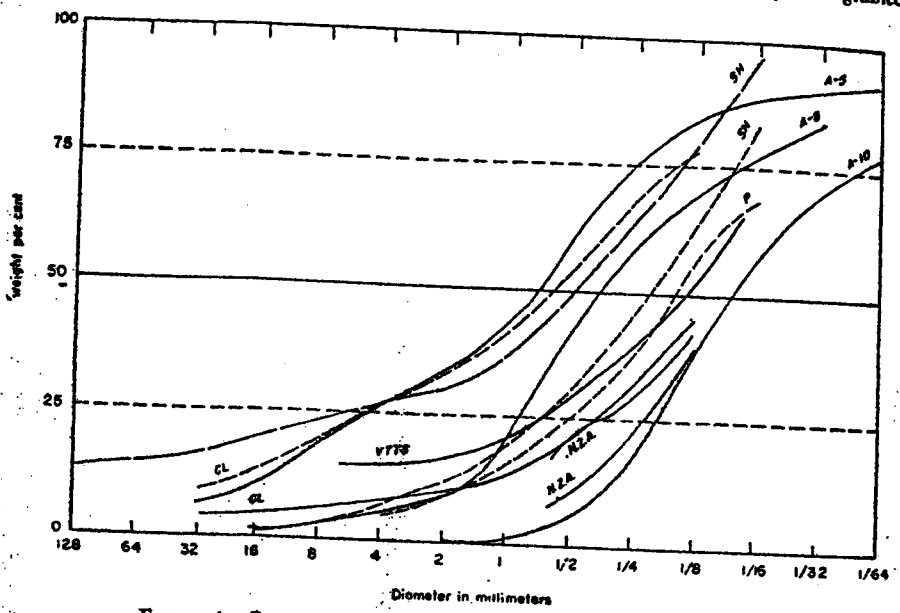


FIGURE 4.—CUMULATIVE CURVES SHOWING SORTING IN ASH FLOWS
SH curves: "Shirasu" deposits, South Kyushu, Japan (Taneda, 1954; 1957; Taneda, Miyachi, and Nishihara, 1957)
A curves: Asama volcano, Komoro deposits, Japan (Tsuya, Murai, and Hosoya, 1958)
CL curves: "Older pumice," Crater Lake, Oregon (Moore, 1934)
VTTS curve: "Sand flow," Valley of Ten Thousand Smokes, Alaska (Fenner, 1923)
P curve: "Sillar" near Arequipa, Peru (Jenks and Goldich, 1956)
N.Z.A. curve: Nonwelded portion of "ignimbrite," Arapuni, New Zealand (Marshall, 1935)

Seemingly there is no obvious correlation between sorting and volume of deposit, composition, type of vent, or source area. The data, therefore, do not supply criteria for separating ash flows erupted from craters from fissure eruptions. Statistical studies of a large number of deposits might show that there is a tendency for rhyolitic or fissure-erupted material to be finer-grained than others, but even this seems doubtful. The principal differences among the curves shown in Figure 4 seem to be in the variation in amount of coarse materials (pumice fragments above 4 mm) both within a single deposit and in different deposits.

The data suggest that even within the framework of the cumulative curves (Fig. 4) there is considerable room for variation, and detailed studies from many deposits should yield use-

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Idaho, studied by Mansfield and
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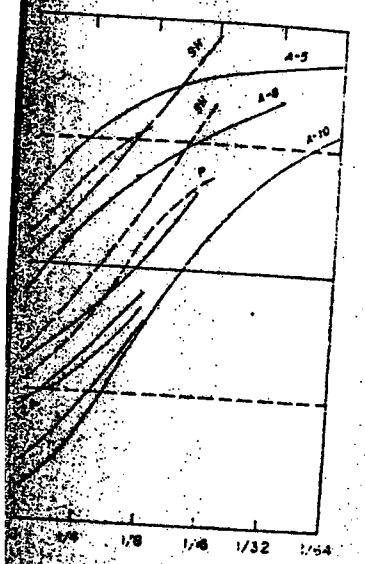

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ful data. If, for example, a variable vertical component plays a significant role in these eruptions, then we have a mechanism that can influence sorting features *before the ash flow is formed*. Crystal enrichment or, rather, fine glass shard and dust impoverishment might take place in the eruptive column giving rise to ash flows that are not strictly representative of the magma from which they were formed. Comparative studies of bulk crystal–glass ratios in the flows, and of crystal–glass ratios in the pumice fragments should be made wherever possible. Studies contrasting nonwelded ash flows with the nonwelded facies of densely welded gas-rich ash flows might supply information on the role of gases in reducing attrition and sorting during emplacement, and might also further our understanding of the pyroclastic-flow mechanism.

A few writers have considered attrition during flowage to be responsible for the high proportion of fine ash in these deposits. Whether or not this is true remains to be demonstrated. It does not seem possible that such a mass of fragmented material could flow for miles without considerable attrition (especially near the distal end), yet if attrition does take place there should be a marked increase in amount of ash and fine ash from source to distal end of the flow. There are, as yet, no really diagnostic data bearing on this facet of the problem. Although Moore's (1934, p. 365) data suggest that there is an increase in material smaller than 4 mm away from the source, in the Crater Lake pumice flows this may be due to sorting. Williams (1942, p. 82) states that the size of pumice lumps bears no relation to distance from the source although they are generally more rounded at the distal ends. Krumbein and Tisdel (1940, p. 304) have shown that the sorting characteristics of the Crater Lake "pumice flows" conform to Rosin's law of crushing, a fact which may have some bearing on our interpretation of the pyroclastic-flow mechanism. It probably remains to be determined whether explosive disintegration and attrition produce the same sorting characteristics. The sorting characteristics of lahar (volcanic mud flow) deposits are very similar to those of ash flows, but perhaps of generally coarser grain.

Welding

The sticking together, cohesion, or welding of fragments of tuffaceous rocks was recognized by Fritsch and Reiss (1868, p. 414), Zirkel (1876, p. 267), and Dell'Erba (1892) long before Iddings (1899) introduced the term "welded pumice." The term "welded tuff", commonly incorrectly credited to Iddings, probably evolved from Iddings' use of "welded pumice." It was first formally introduced by Mansfield and Ross (1935), although Ross (oral communication) says that "welded tuff" was in use in the U. S. Geological Survey long before 1935. His first recollection of using the term was in 1919 in connection with rocks in the eastern San Juan Mountains near Crestone, Colorado. Their origin was then a puzzle, but we now know from re-examination that these rocks are densely welded tuffs of ash-flow origin.

The welding process as it applies to ash-flow materials promotes the union or cohesion of glassy fragments in a viscous state. The degree of welding may range from incipient stages marked by the sticking together or cohesion of glassy fragments at their points of contact to complete welding of the surfaces of glassy fragments accompanied by their deformation and by the elimination of pore space, and perhaps ultimate homogenization of the glass.

Phenocrysts and rock fragments are rarely affected by the welding process nor do they have much effect on it, except in rare instances where they are so abundant as to inhibit consolidation of the glass fragments.

Many variables affect the degree of welding; the more important ones are (1) temperature, (2) amount and composition of volatiles, (3) composition of ash, (4) lithostatic load, (5) rate of cooling, and (6) rate of crystallization. The first three control the viscosity of the glass and for purposes of discussion may be reduced to the one variable, viscosity. Lithostatic load is a function of density and depth in the deposit. The load pressure and the viscosity control the rate of loss of pore space which really is the only measure of rate of welding. We thus see that the degree of welding, in an ash flow, is dependent on three rate processes: the rates of welding, cooling, and crystallization. Crystallization is also related to the viscosity of the glass.

Of all the variables that control the cooling history of ash flows the two most important are probably emplacement temperature and the thickness of the flow or cooling unit. Because these influence all the others, or are in some way related, it is possible to interpret the observable variations in the flows in these terms. In ash flows, emplaced at approximately uniform temperature throughout, the rate of

welding will be faster at or near the base of the unit and will decrease toward the top. For this reason the transition between densely welded tuff and nonwelded tuff will invariably be much sharper in the lower part than in the upper part of a simple cooling unit. All transitions are sharper in high-temperature ash flows than in low-temperature ash flows.

In its simplest form, the welding process is the merging of viscous glass particles into a coherent mass. In very young and fresh ash flows that have not crystallized, the incipient stages of welding are marked by the first signs of coherence and brittleness in the transition from unconsolidated to obviously indurated material. In older and less fresh rocks and those which have crystallized, we must depend on visible deformation of pumice fragments or shards as a criterion for welding. From the incipient stage there is a complete gradation with progressive loss of pore space, deformation of pumice and shards, and darkening to a dense black glass. During the color change, the darkening of the pumice lumps usually precedes the darkening of the shardy matrix. The contrast emphasizes the well-known eutaxitic structure characteristic of so many welded tuffs, especially in those of low porosity (0 to 25 per cent).

The formation of a black glass appears to be the end product of the welding process; however, with aid of the microscope, an additional change becomes apparent—the gradual obliteration of vitroclastic and vesicular structures. This process begins in the collapsed pumice fragments, removing all trace of vesicular structure, and it finally extends to the shard boundaries. In some welded tuffs vesicular structure in pumice has been obliterated before the black-glass stage is reached. Elimination of all pumice structure is rare but has been noted (Ross and Smith, in press), whereas the elimination of all shard boundaries in glassy welded tuffs is not known to the writer. The elimination of all traces of shard boundaries is not achieved because of the original dusty matrix between the shards, a problem not presented by the pumice vesicles. Homogenization of all the glass shards and pumice is, then, the probable ultimate end of the welding process and will probably require an exceptionally hot, thick ash flow for its fulfillment.

Welding Temperatures Determined by Experiment

Many early workers have experimented with melting, vesiculation, and crystallization of volcanic glasses, but the first attempt to make welded tuffs by welding fragmental volcanic glass was by Boyd and Kennedy (1951, p. 327). They found that crushed rhyolitic pumice from Mono Craters, California, welded at temperatures ranging from 775° to 900° C. In later work Boyd (1957, Ph.D. Thesis, Harvard Univ.) found that the presence of water vapor effectively lowers the welding temperature. Glassy rhyolitic volcanic ash from Yellowstone Park was sealed in platinum capsules with water equivalent to 0.45 weight per cent and held for 80 hours and a pressure of 52 bars. The minimum welding temperature under these conditions was between 590° and 620° C. Increasing the time of the experiment to 2 weeks resulted in lowering of the welding temperature to between 550° and 590° C. Boyd found that the same ash, dehydrated and without addition of water in the experiment, showed slight welding at 690° C. after 72 hours at a pressure of 48 bars, and no welding at 655° C. From these and other experiments Boyd concluded that the minimum welding temperature in the presence of water vapor is about 600° C.

Smith, Friedman, and Long (1958, p. 532-533, and unpublished data) found very similar results. The method used differs from Boyd's in that the charge of unconsolidated ash was placed in a platinum-lined copper container which was in turn placed in a bomb fitted with an adjustable piston through its top. Load pressure was applied directly to the surface of the charge by the piston assemblage. A lever arm that applies load to the piston was attached to a recorder, and the rate of compaction was measured. Water pressure in the bomb was controlled externally, and the water content of the welded pellets was later measured directly or determined by analogy to quenching experiments made on crushed obsidian hydrated at different temperatures and pressures. The ash used in the welding experiments was from a nonwelded facies of the Bandelier rhyolite tuff, Valles Mountains, New Mexico.

The minimum temperature for incipient welding was below 535° C. and is controlled largely by temperature and water-vapor pressure, whereas complete welding is dependent on these variables plus load pressure and time. Time is limited by crystallization and cooling, but these factors have not yet been assessed. No satisfactory minimum temperature for complete welding (black glass) has yet been found, although it is below 635° C. at 528 p.s.i. load pressure, 300 p.s.i. water-vapor

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it is below 635° C. at
300 p.s.i. water-vapor

ure, and 50 hours time. Fifty per cent
paction was reached in one run, in about
s, at 535° C., 528 p.s.i. load pressure, and
p.s.i. water-vapor pressure. Further, for
flows of the order of 100 feet thick or less,
peratures above 735° C. probably are
ssary for the formation of a densely welded
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Ameda (1957, p. 99–100) reports welding
riments on the "Shirasu" (white sand), a
mice-flow" deposit associated with Aira
era, South Kyushu, Japan. He found that
n heated in an electric furnace in the
perature range of 600° to 1200° C. in 1 to
hours it changed color from "gray white to
dish or purplish gray, a reddish tinge being
pened with raising temperatures from
600° to 1000° C." Melting began between
800° and 920° C., and at 1200° C. melting was
entially complete and the original color was
stored. "Load-bearing tests of pumice" were
ade in the temperature range 600° to 1000° C.
d at loads of 1, 3, and 5 kg/cm², the latter
corresponding to 30 m depth in the "Shirasu" bed.
It was concluded that the "Shirasu" would
old below 920° C. to look like "Hai-ishi"
welded tuff associated with "Shirasu") and
at the nonwelded "Shirasu" could not have
en emplaced above 900° C.

Because the "Shirasu" would contain little
no water at the temperatures of these
periments, and because the times were very
ort, it is doubtful whether or not they could
ply strictly to the natural materials. Probably
me welding would take place in "30 meter
ick beds" at temperatures considerably
low 900° C.

Compaction during Welding

Surprisingly few references have been made
the total compaction of ash flows during
elding, although compaction may reach
ologically significant proportions in some
atigraphic sections of densely welded tuff.
e compactibility is related to the bulk
rosity and therefore to the ratio of pumice
solid material. In most ash flows the initial
lk porosity must be greater than 50 per
t. This is not shown by published porosity
density curves, probably because of the
ficulty of collecting and measuring repre-
tative samples of unconsolidated material,
ecially in older rocks.

The specific gravity and porosity curves for
lded ash flows shown in Figures 5 and 6 are
only ones available. In addition to these curves Weyl (1954, p. 18, 21) gives specific-gravity figures ranging from 1.28 to 2.03 for rhyodacite tuffs from the Comalpa area and from 1.21 to 1.89 for dacitic tuffs from the Zaragoza area, El Salvador. These have not been plotted in Figure 5 because the positions of the samples were not given. The figure of 1.28 for the Comalpa tuff probably represents a bulk porosity of about 50 per cent, whereas the figure of 1.21 for the Zaragoza tuff implies over 50 per cent porosity, perhaps 55 per cent to judge from Weyl's chemical analysis. These figures seem more realistic than others published for fresh unconsolidated ash-flow materials as do the figures 0.98 (specific gravity) and 60 per cent (porosity) given by Lovering (1957, p. 1587, 1593) for the Valley of Ten Thousand Smokes "sand flow." Ross and Smith (in press) found 70 per cent porosity for part of the Battleship Rock ash flow, New Mexico. Smith, Friedman, and Long (1958) found by experiment that the compaction potential of unconsolidated material, mostly less than 4 mm in size, for the Bandelier rhyolite tuff from New Mexico is approximately 50 per cent This material was used for making synthetic "welded tuffs" and represents only the finer-grained part of the Bandelier tuff, the bulk porosity of which is considerably greater than 50 per cent.

The data indicate that where measured porosity curves show maximum porosities less than 50 per cent, they should be extrapolated to at least 50 per cent if they are to be used for studies involving thicknesses of zones or cooling units, compaction, or similar problems. Pure shards or crystals probably have a bulk porosity of about 50 per cent, and most ash flows contain pumice which commonly has 70 or more per cent pore space in rhyolitic rocks. Roughly then, an ash flow containing 50 per cent by volume of pumice or pumiceous ash of 70 per cent porosity and 50 per cent shards would have a bulk porosity of 60 per cent and a specific gravity of about 0.94 if it were 100 per cent glass, or about 0.99 if it were 50 per cent crystals of sanidine and quartz. The ratio of crystals to glass will not cause significant variation in the bulk density of unconsolidated ash, except in very mafic rocks.

Because most ash flows contain some pumiceous materials but probably not more than 50 per cent we can expect that they will have initial porosities between 50 and 60 per cent. Obviously, an ash flow having 60 per cent pore space could compact to a welded tuff having less than half the original thickness. Probably very few entire sheets have undergone such

compaction. Those in which it has occurred would have been very hot, thus more thoroughly welded, or very thick allowing a thick zone of dense welding to form, or, rarely, may have had exceptionally high initial porosity. For simple cooling units that contain densely welded tuff it is possible to get an approximate figure for the thickness before welding without density or porosity measurements, if the thicknesses of the three basic zones (*see* section on Zones and Zonal Variations) are known. Assumption of 50 per cent initial porosity probably gives the figure closest to a minimum. The calculations: 2 times the thickness of zone of dense welding plus 1½ times the thickness of zones of partial welding plus the thickness of zones of no welding equals total thickness before welding. This method is subject to some error but is a useful approximation.

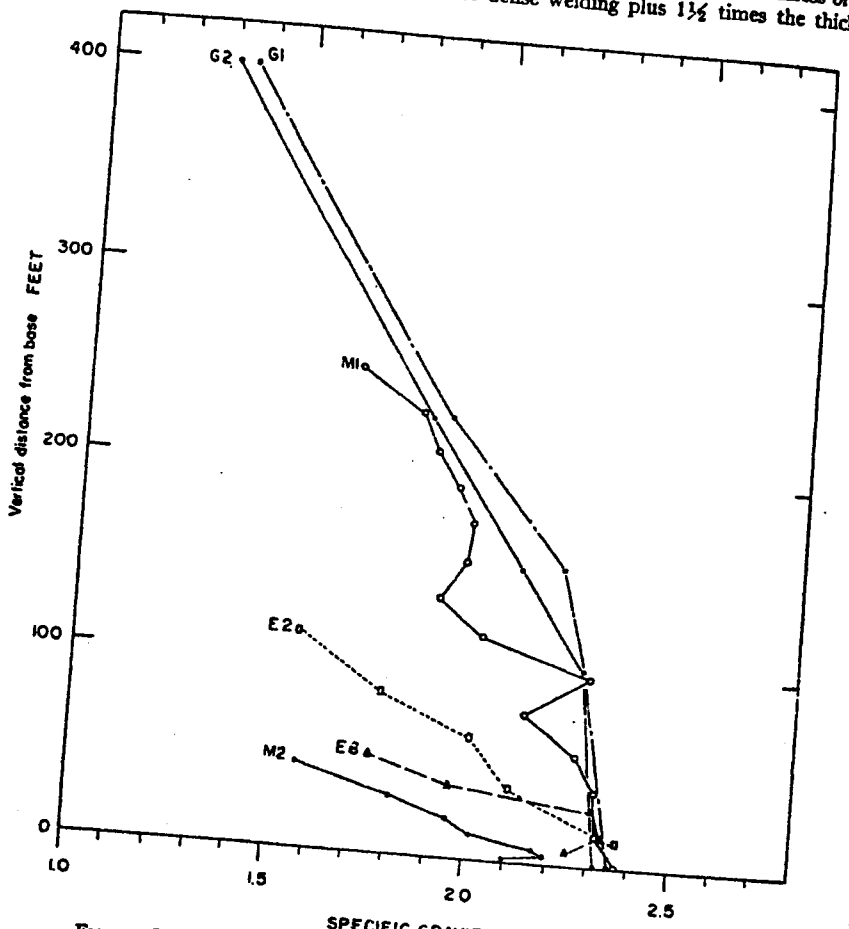

FIGURE 5.—SPECIFIC-GRAVITY CURVES FOR WELDED-TUFF SHEETS
G curves: Bishop tuff, California (Gilbert, 1938)
M1 curve: Motutere "ignimbrite," New Zealand (Marshall, 1935)
M2 curve: Arapuni "ignimbrite," New Zealand (Marshall, 1935)
E curves: Chiricahua "welded tuff," Arizona (Enlows, 1955)

Crystallization

Crystallization during cooling in pyroclastic deposits was noted by Zambonini (1919) who

described several unusual fluorine-bearing minerals from the classical Italian piperno. Fenner (1937, p. 236) found tridymite and

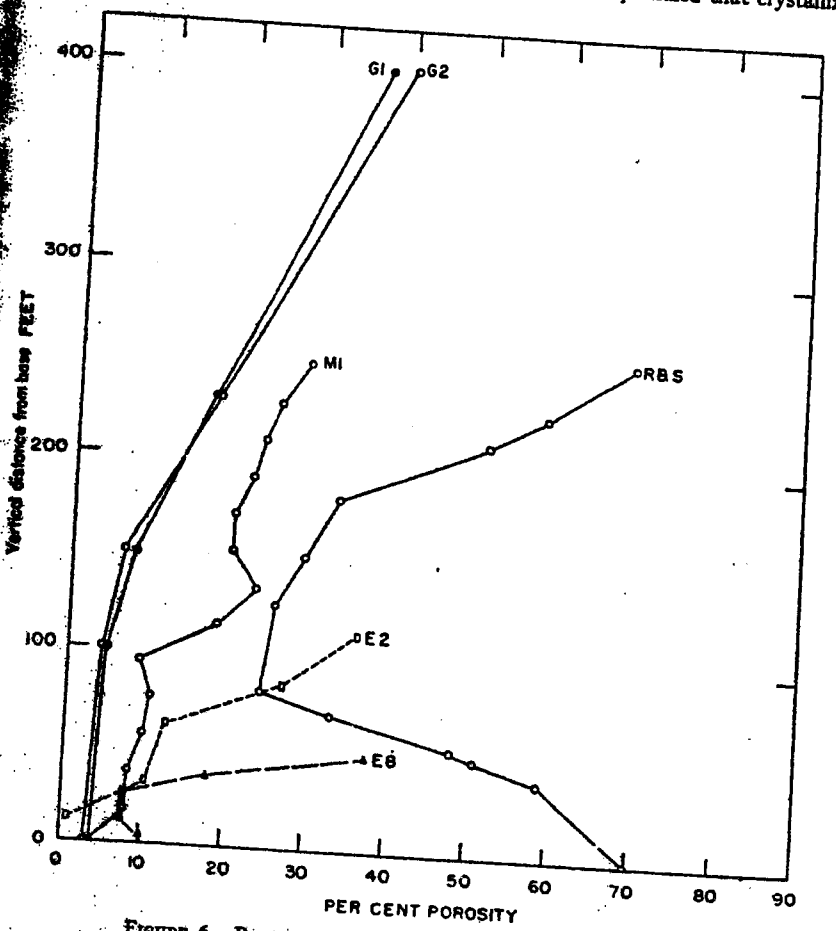

FIGURE 6.—POROSITY CURVES FOR WELDED-TUFF SHEETS
G curves: Bishop tuff, California (Gilbert, 1938)
M1 curve: Motutere "ignimbrite," New Zealand (Marshall, 1935)
E curves: Chiricahua "welded tuff," Arizona (Enlows, 1955)
R and S curve: Battleship Rock "ash flow," New Mexico (Ross and Smith, in press)

between depth and cooling rates and the type of crystallization structures formed. Gilbert (1938, p. 1856) emphasized that crystallization in the upper part of the Bishop tuff sheet was influenced by rising gases. Westerveld (1942, p. 211–212) has described the effects of "pneumatolytic" crystallization in the Pasoemah tuffs, South Sumatra, and Toba tuffs (1947, p. 34), North Sumatra.

Fenner (1948, p. 883) proposed that induration in the Cordillera tuffs of Peru was due primarily to pneumatolytic "recrystallization"

rather than "softening" and union by welding, and that such tuffs should not properly be called "welded tuffs." Fenner proposed the local Peruvian name "sillar" to cover these materials. Jenks and Goldich (1956) restudied these tuffs in more detail but agreed essentially with Fenner's views. No one who has studied both the "sillar" type tuff and densely welded tuff would confuse the two in their optimum state of development or question Fenner's need for distinguishing the two, even though in some deposits they are transitional. However, we should perhaps question the reasoning that leads to the conclusion that the induration was the result of crystallization rather than welding.

We may seriously doubt that the crystallization of the vapor-phase mineral assemblages, sanidine-tridymite or sanidine-cristobalite in the "sillar" type tuffs, was *initiated* below the minimum welding temperature of the tuff (<550° C.). If this be admitted then ash flows that show crystallization must also be mildly welded if they are thick enough to show even mild deformation of pumice or shards. Some compaction could be expected without visible deformation of shards of pumice, resulting in an incipiently welded coherent rock which after crystallization would no longer show that it had once been mildly welded. However, the writer has observed that coarse vapor-phase crystallization will render an incipient to mildly welded tuff less coherent after crystallization. The comparison can be made between fresh and unaltered glassy and crystalline rocks, judged to be otherwise equivalent, in which the first visible traces of compaction folliation have appeared. The crystalline "sillar" is the more crumbly. It is also less resistant to erosion. Some specimens of Peruvian "sillar" as well as other "sillar" type tuffs show compaction foliation.

We cannot question the fact that crystallization of unconsolidated ash and pumice would result in material more coherent than it was before crystallization, but we can suggest that most completely crystalline "sillar" was a coherent, albeit porous, rock, owing to welding before it crystallized.

Ross and Smith (in press) have shown by X-ray studies that cristobalite rather than tridymite is the common form of silica, where crystallization has been confined to the glass shards or welded glass masses. Tridymite, on the other hand, is more common as discrete crystal or crystal aggregates in pore space where its crystallization is believed to be related to active vapors. Two distinct types of crystallization are suggested: (1) devitrification—characterized by intergrowths of cristobalite and alkalic feldspar, mainly in axiolitic and spherulitic growths but also in some "closed" lithophysal cavities; and (2) vapor-phase crystallization—characterized by growths of tridymite, alkalic feldspar, and other minerals in pore space. Porous axiolites and spherulites may contain tridymite, but this simply means overlapping of two processes. In general, the tendency for tridymite to form increases with the degree of porosity of the groundmass of the tuff within the crystalline portion. In some welded tuffs tridymite does not occur, yet cristobalite is common to all crystalline welded tuff sheets that have not undergone diagenetic or other metamorphic changes. In these older or altered rocks quartz replaces the other silica minerals.

Nearly all writers who have studied the products of cooling-history crystallization in welded tuffs have identified alkalic feldspar and at least one of the polymorphs of silica as the principal minerals formed.

SILICA MINERALS: Tridymite, ordinarily easily identified with the microscope, is the silica mineral most frequently mentioned, and, although it is a common mineral in many welded tuffs, it has probably been mistaken for cristobalite in many descriptions. Cristobalite has been recognized by Zavaritsky (1947), Williams (1952, p. 173), Bailey (1957), and Martin (1959, p. 404).

Enlows (1955, p. 1230) reports quartz as the common groundmass silica mineral in Member No. 6 of the Rhyolite Canyon formation, based on X-ray study. He states that tridymite was not found. The writer has been somewhat reluctant to accept most interpretations of quartz as a primary groundmass mineral in welded tuffs. It seems that it is far more common in older and more obviously altered rocks, whereas in fresh Pleistocene and Recent rocks it has not been recorded. By analogy to thick rhyolite flows it should occur in some thick sheets of welded tuff. The writer is now convinced that primary groundmass quartz should occur in any simple cooling unit of rhyolitic composition more than about 600 feet thick. The necessary thickness for the formation of quartz will no doubt vary with emplacement temperature, vapor pressure, and perhaps other factors. Enlows' Member 6 is 880 feet thick, and there seems little doubt that the quartz reported by him is primary; however, this quartz should give way at least in the upper part of the sheet to cristobalite

perhaps tridymite, unless these minerals been replaced by secondary quartz.

blems of this type need a much more ough investigation before we can arrive at sound generalizations. The writer (Smith, ess) has proposed that the distribution of lica minerals is zonal and is related to and degree of welding within simple g units.

DSPARS: Very little can be said about the dmass feldspars in crystallized welded and systematic studies using modern techniques have not been made. Feldspar as discrete crystals or crystal aggre- with tridymite in the vapor-phase zones, hmicroscopic intergrowths with cristobal- n devitrified zones, and as granophyric rowths or discrete miarolitic cavity ls with quartz.

sterveld (1942, p. 211) and Martin (1959, 4) reported albite; Gilbert (1938, p. 1845) Enlows (1955, p. 1230) reported sanidine; (1948, p. 883), orthoclase or natro- ne; many other writers have reported lic" or "alkali feldspar," "potassium ar," or simply "feldspar."

obably in most silicic welded tuffs the dmass alkalic feldspar is a form of ne that probably bears a relation to the composition of the host rock. It is sug- that it was formed above the solvus rature unless it be admitted that it form metastably, as do tridymite and balite. This suggestion is prompted by act that, in some thick cooling units, crystals of sanidine have exsolved to or microperthites.

feldspars also probably bear a systematic onship to their position within the cooling Detailed studies of specific units may be helpful in formulating a framework for of crystallization temperatures.

bert (1938, p. 1850) reported overgrowths anidine on sanidine phenocrysts in the parts of the Bishop tuff where they were mably deposited by rising gases. Similar are found in some "vapor-phase zones" Bandelier tuff, New Mexico.

ER MINERALS: Minerals other than the pars and silica minerals that form during dmass crystallization are not well known. the more common are magnetite, e, fayalite, and sodic amphibole. These form deep within cooling units. Another of near-surface and surface fumarolic ls, including magnetite, are known from the work of Fenner, Allen, and Zies in the Valley of Ten Thousand Smokes, Alaska (Zies, 1929). Most of these are halides, sulfates, and sulfides of metallic elements. Magnetite has also been recorded as a fumarolic mineral by Mackin (1952, p. 1337–1338), Williams (1942, p. 86–87), and Gilbert (1938, p. 1851).

Behavior of Phenocrysts and Inclusions during Welding and Crystallization

It has not been shown that the welding process *per se* has caused changes in phenocrysts in any rocks yet described; however, crystallization processes and the rate of cooling do cause changes in individual crystals of some welded tuffs. Sanidine phenocrysts undergo changes, in optical properties and degree of unmixing to cryptoperthites, which are related to the cooling history of given vertical sections. The catalytic effects of hot vapors may facilitate these changes. Boyd (1957 Ph.D. Thesis, Harvard Univ.) has made the only quantitative X-ray study of unmixing of sanidine which shows in the Yellowstone welded tuffs a clear-cut relationship to position in the unit. In a qualitative way the unmixing phenomena in sanidine can be observed in some welded tuffs by the change from clear "glassy" sanidines in the chilled portions of the units to chatoyant ones (moonstones) in the more slowly cooled parts. This is a common phenomena in the Bandelier tuff, Valles Mountains, New Mexico, and the writer has observed it in other sanidine-bearing welded ash flows.

Whereas unmixing is detectable in some sanidine phenocrysts under the microscope, particularly those from very thick cooling units, it does not resemble the unmixing to coarse microperthite seen in the smaller, thinner sanidine crystals formed in cavities during cooling of the same unit. An excellent example illustrating this difference in degree of unmixing is a specimen the writer collected from Bonita Canyon, Chiricahua National Monument, Arizona. These rocks were described by Enlows (1955), and the specimen is from Enlows' Member 6 for which he gives a thickness of 880 feet. Chatoyant sanidine phenocrysts show only faint visible traces of unmixing, but chatoyant tabular "sanidine" crystals from miarolitic cavities are coarse microperthite.

Biotite and hornblende, commonly green to shades of brownish green in chilled glassy parts of ash flows, are often changed to deep red brown or sometimes completely destroyed in the crystalline parts of welded ash flows.

The degree of destruction seems related to the intensity of vapor-phase activity within units of given compositions, and the thickness of the cooling unit plays a major role in controlling intensity of vapor-phase activity. This deuteric or vapor-phase alteration ranges from a very minor role in some cooling units to a major one in others. Where it was intense nearly all minerals and inclusions, except possibly zircon and similar accessory minerals, show some effects, although commonly no more than border corrosion. Specifically the writer has observed varying degrees of alteration or corrosion in phenocrystic quartz, sanidine, plagioclase, amphibole, clinopyroxene, orthopyroxene, fayalite, and sphene.

No systematic studies of these alteration effects have been made, and they are another interesting field of inquiry. Excellent examples of biotite and hornblende alterations are found in welded quartz latite ash flows throughout the Basin and Range province. Some of these from southwestern Utah and adjoining parts of eastern Nevada have been studied by Mackin (1952, p. 1338, and oral communication), and by Cook (1957, p. 57).

Zones and Zonal Variations

Nearly all workers since the 1930's who have recognized the fundamental pyroclastic nature of welded tuffs have also observed and described systematic textural changes, particularly in vertical sections, within given units. Probably all significant textural variations that occur among welded tuffs have been found and described (Marshall, 1935; Mansfield and Ross, 1935; Gilbert, 1938; Enlows, 1955). Most of these can be seen in the illustrations of Ross and Smith (in press), Smith (in press), and Martin (1959). Good illustrations of marked secondary flowage features have not yet been published.

It is improbable, but not inconceivable, that all the important known textural variations resulting from welding and crystallization could be found in the same composite sheet. Most of them are possible in simple cooling units. This fact makes it difficult to classify welded tuff sheets on a purely descriptive textural basis. Most of the available descriptions are based on one or a few vertical sections which probably only rarely characterize the three-dimensional sheet. It is true that some welded tuff sheets at first glance seem to be monotonously uniform over great areas and different enough from other welded tuffs to be considered distinct types. For example, it would be improbable for the Walcott tuff (Stearns and Isotoff, 1930, p. 23) to grade laterally as the same flow unit into a crystalline tuff of the Peruvian sillar type. However, it might merge with a cooling unit which contains crystalline sillar-type material and there lose its identity as densely welded crystalline, rather than vitric, welded tuff, without the lithophysae and spherulites that now characterize it in the section at American Falls, Idaho. Thickening of the American Falls section from 25–50 feet to 75–100 feet (as a simple cooling unit) would unquestionably have resulted in the formation of a persistent crystalline zone which might predominate over the present glassy section.

In contrast to the Walcott tuff, which shows dense welding in a 25-foot thick unit, the Battleship Rock ash flow (Ross and Smith, in press) shows no dense welding in a cooling unit about 250 feet thick, but its initial porosity of about 70 per cent has been reduced to less than 25 per cent in the zone of maximum deformation, and no crystallization has taken place during cooling. The Walcott tuff, on the other hand, shows incipient crystallization in the form of spherulites and lithophysae and clearly was emplaced at the higher temperature. Clearly the evidence presented by these two sheets, together with such data as are available from other sheets, indicates a relationship between the emplacement temperature, the degree of welding, the thickness of the sheet, and the retention of the glassy state during cooling. For any given temperature of emplacement there is apparently a corresponding maximum thickness of the simple cooling unit below which no crystallization will take place during cooling. It is not anticipated that composition, gas content, or cooling rates in different environments will, in general, show differences great enough to invalidate this generalization for gross comparisons.

In a general way, maximum vitric cooling units emplaced at high temperature are thinner, more densely welded, and show sharper transitions between nonwelded and welded material than the maximum vitric cooling units emplaced at lower temperatures. Thicknesses greater than the maximum vitric unit for any given temperature will result in crystallization, incipient at first (Walcott tuff of American Falls, Idaho) but persistent as a continuous zone of crystallization at greater thicknesses. This zone exhibits an increasing number of facies as the unit thickens further. These different facies or zones of crystallization are

to the degree of welding of the tuff on they are superimposed as well as to ositions within the units and to other

h (in press) has attempted to show the relations between thickness, tempera- nd the formation of textural and struc- ones by means of hypothetical diagrams. basic zones are recognized: (1) the zone welding, (2) the zone of partial welding, 3) the zone of dense welding. Where welding occurs in a unit, the other two have upper and lower counterparts merge with lateral thinning or near the s of the sheet. The lower zones of no g and partial welding are thinner than per ones in simple cooling units and may ally absent owing to special or extreme ions of temperature and pressure. llization superimposed on the basic may be recognized as (1) the zone of fication, (2) the zone of vapor-phase llization, (3) the zone of granophyric llization, and (4) the zone of fumarolic tion.

s scheme of representation is largely ative, but, with the accumulation of le measurements of the various zone nesses and positions within a variety of g units, it may develop into a quantitative ne leading to the solution of problems of loss during emplacement, emplacement eratures, rates of cooling, direction of e, and many others. In future studies gists should, if possible, record the zonal cteristics, especially of complete cooling- sections, quantitatively. The zonal patterns mple cooling units must be understood e we can hope to evaluate compound g.

Deposits Emplaced at Low Temperature

flows probably can be emplaced at any erature up to a maximum eruption erature, perhaps of the order of 1000° C. e minimum welding temperature is taken about 500° C., there is a wide temperature through which endless variations can

are not yet able to correlate specific ash with specific temperatures, but a gross ive scale is possible. Because thickness is a important factor in controlling degree elding, many thin ash flows emplaced their potential minimum welding tem- ure do not show welding. These are ordinarily not distinguishable from deposits emplaced below their minimum welding temperature, although the presence of a red zone caused by oxidation of iron probably indicates a higher temperature. Ferromagnetic properties may be useful in distinguishing nonwelded ash flows emplaced above the minimum welding temperature which is close to the Curie point.

The designations high, low, and intermediate must be arbitrary and are only expedient subdivisions for ordered discussion.

Low-temperature deposits, then, are those in which little or no welding or crystallization is apparent in thick cooling units. These include deposits such as the Crater Lake and Krakatoan pumice deposits, the "Shirasu", and many others. Because some ash-flow fields contain units emplaced at high, low, and intermediate temperatures (Pl. 2, fig. 2), but presumably were derived from the same magma and erupted at the same temperature, the low-temperature deposits offer the best evidence for a cooling mechanism before the ash flow is formed. (*See* section on Vertical Component.)

Deposits Emplaced at High Temperature

Perhaps the best examples of high-temperature deposits are those from Idaho (Mansfield and Ross, 1935; Stearns and Isotoff, 1956). These rocks occur in sheets ranging from 15 to 50 feet thick and contain a zone of densely welded tuff to within a few feet of the surface and locally a zone of fused air-fall tuff at the base. These facts attest to their high temperature of emplacement. A high magmatic temperature is suggested by the paucity of phenocrysts. Probably these materials were derived from very hot and very dry magmas. Obsidian formed in the welded tuff from the Ammon quadrangle (Mansfield and Ross, 1935, p. 319–321; Ross and Smith, in press) has a water content of 0.15 per cent, similar to many normal obsidians of rhyolite flow or dome origin. The Walcott tuff of Stearns and Isotoff (1956), considered by Mansfield and Ross (1935, p. 310) to be equivalent to the tuffs studied by them, has been restudied by H. A. Powers (oral communication), who reports water values for the obsidian facies as low as 0.06 per cent. Water contents of this order are probably the lowest known for volcanic glasses and give further indication of the high emplacement temperature if not the low-water content of the magma.

Mansfield and Ross (1935, p. 312) considered that the tuffs described by them had been

emplaced by a great air-borne cloud of incandescent particles and cited as evidence the act that the tuff occurred at different elevations, without significant change in thickness, over a vertical relief of over 2500 feet. The distribution of the tuff suggested that it had been sprayed or "ducoed" over the irregular surface. This connotation has been widely cited in the literature and should be re-evaluated. C. S. Ross (oral communication) no longer holds this view; he now thinks these tuffs were formed from normal ash flows, and that their distribution may be explained by post-emplacement deformation.

Because these welded tuffs are an important link in the development of present-day concepts, they should be restudied. The possibility that, as normal ash flows, they were deposited with very low initial dips, probably less than 2°, might be critical to the interpretation of the geology of the very large area covered by these tuffs. Mansfield and Ross (1935, p. 311) have suggested that this might be of the order of 3000-5000 square miles. The very steep dip of 24° shown by them in one of Mansfield's (1935, p. 310) stratigraphic sections seems incompatible with a primary dip for a welded tuff sheet and suggests that at least part of the sheet has been deformed.

Deposits Emplaced at Intermediate Temperatures

Most welded ash flows are in the intermediate-temperature category. Depending on thickness, there are all degrees of welding and crystallization within this group of rocks. Thin cooling units look like low-temperature deposits, and parts of thick cooling units are not distinguishable from high-temperature deposits. Perhaps the key to relative emplacement temperature is the thickness of the upper zone of partial welding in simple cooling units. This should vary systematically between low and high temperature, but for comparisons between two units it must be equated with initial emplacement thickness or expressed as a ratio to the collapsed thickness.

On the low-temperature side of the intermediate-temperature category are the thick vitric cooling units that show moderate welding, whereas on the high-temperature side are the relatively thin cooling units that show crystallization, a zone of dense welding, and probably a weakly developed and thin vapor-phase zone. The vapor-phase zone, including the crystalline "sillars," probably forms in an optimum temperature range within this intermediate category.

The vapor-phase zone requires a porous matrix for its formation (Pl. 1). At increasingly higher temperatures, the zone of dense welding would probably thicken, whereas the porous upper zones would thin, until they become a part of the "chilled" vitric mantle of the sheet, leaving no space for the formation of the vapor-phase zone. In these higher-temperature rocks the vapor-phase zone would probably give way to a zone of lithophysae in thin units or to a zone of miarolitic lenticles in thick units. Composition, however, becomes important to the problem at this point, and, in general, more basic deposits show less crystallization throughout than do the rhyolites.

Deposits that Record a Change in Temperature

Some ash-flow fields, perhaps many, record variations in emplacement temperature as shown by the different degrees of welding and of crystallization of individual flows or cooling units of equivalent thicknesses. The indicated changes in temperature are particularly significant in areas where all units have a common source. The change may be recognized within a cooling unit or in two or more units. Changes found by the writer appear to be, for the most part, systematic, indicating a general increase in emplacement temperature in successive flows.

Weyl (1954, p. 17–23) has described dacitic and rhyolitic welded tuff deposits from the Zaragoza and the Compalpa regions of El Salvador, respectively. They are of the order of 100 m thick and decrease in density from the top to the bottom. Weyl has noted the difference between these and other welded tuff sheets which increase in density toward their base. Weyl (1954, p. 27) suggests that the earlier "nuées ardentes" brought forth relatively cool material, whereas the later ones carried progressively hotter material that was more susceptible to welding.

We cannot tell, from Weyl's description, the specific type or types of units represented by either the Comalpa section which is 100 m thick or the Zaragoza section which ranges from 30 to 100 m, but the inference is that the changes he noted from top to bottom of both sections are continuous and progressive. The Comalpa section shows a range in specific gravity from 2.03 near the top to 1.28 at the base, accompanied by a change from obvious welding at the top to no welding at the base.

ystematic changes of the type described by
may be explained in several ways depend-
on the kind of units involved. If the changes
related to differences in emplacement
peratures, they may represent a change in
ma temperature as progressively lower
ls of the magma chamber are drained during
eruption, or they may represent progres-
ly more efficient conservation of heat during
formative stages of successive ash flows.
he detection of evidence for changes in
placement temperature in successive units is
cult in many deposits. Variable thicknesses
flow units, the order in which they are
cked, and the length of time between succes-
flows can create compound cooling units
which systematic emplacement-temperature
nges are not obvious and in which apparent
nges are not real. Deposits may eventually
found that show an increase in density and
ree of welding from top to bottom, but
ch were formed by stacking of successively
ter thinner flows.

Deposits that Record a Change in Composition

Deposits from a common source that record a
nge in composition in successive ash flows
be the most significant of all deposits
logically. These changes are of three kinds:
change in magma chemistry; (2) change in
stal-glass ratio; and (3) change in type of
mate vesicular fragments. A change in
ma chemistry is usually accompanied by
physical changes of (2) and (3) and may be
orded in one compound cooling unit.

The Crater Lake field is probably the best
mple of a change in magma chemistry yet
cribed. Williams (1942, p. 98) states that
total volume of pyroclastic material laid
wn during the culminating eruptions of
Mazama is between 9.75 and 11.75 cubic
les. Six to 8 cubic miles of this consists of
lowing-avalanches" deposits, seven-eighths
which is dacite pumice and ash; the rest is
stal-rich "basic scoria." The silica content
the dacite pumic ranges from 66.4 to 68.9
cent; that of the "basic scoria" from 53.9
56.9 per cent. There are no intermediate
desitic ejecta. Mineralogically the "basic
oria" differs from the dacite pumice in having
re ferromagnesian minerals, hornblende
d olivine, and more calcic feldspar, and
k-brown glass. It also contains more lithic
clusions. Most remarkable is the fact that
transition between the underlying "pumice
ws" and the later "scoria flows" takes place within a few feet (Williams, 1942, p. 83). The transition was sudden, without a detectable time break, and it must be concluded that there was an essentially continuous evolution of material. Locally the "scoria flows" have well-developed columnar structure; the "pumice flows" do not.

Commonly volcanoes that have erupted silicic magma later erupt more basic magma. In most instances we cannot evaluate the changes that took place between eruptions. At Crater Lake there was no time break, and the suddenness of the transition leads us to consider possible conditions in the magma. The continuity of the eruptions that produced the dacite pumice and "basic scoria" suggests they came from a single magma chamber where they must have existed as magmas with a sharp interface. The frequency of formation of simple calderas, like Crater Lake, in composite cones supports the single-chamber hypothesis.

The Crater Lake deposits are probably not unique. Contrasting magmas of rhyolitic and basaltic compositions are known from air-fall pyroclastic eruptions in Iceland. These are very small-volume deposits. Hekla (Thorarinsson, 1954, p. 32–45) is a notable example. In contrast to these the volume (order 5, Fig. 3) of the Crater Lake ejecta is large. The volume of pyroclastic ejecta making up the Bandelier tuff, Valles Mountains, New Mexico, is approximately 40–50 cubic miles (order 6, Fig. 3). The Bandelier ash flows record a change from early high-silica rhyolites to quartz latites at the end of the last ash-flow cycle.

The lavas that preceded the ash flows include quartz latite, rhyodacite, and more basic types.

Even the very large volume (order 7, Fig. 3) deposits may show similar trends. For example, van Bemmelen (1949, p. 694) states that the Toba eruption was preceded and succeeded by andesitic volcanism. The outburst of "granitic magma" was only an interlude in the continuous volcanic activity that normally produced "dioritic" magmas. Van Bemmelen (1949, p. 691) says that the Toba tuffs were probably produced by one, or a short succession of, cataclysmic outbursts, because no distinct stratification has been observed throughout most of the stratigraphic section. Some layering, however, is observed in the higher parts. Is it possible that a change in compositon is recorded?

Both andesitic and rhyolitic magmas were involved in the formation of the "glowing-

avalanche" deposits of the Sudbury basin (Williams, 1957, p. 69); andesitic "avalanches" followed rhyolitic eruptions.

Some ash-flow fields, composite sheets, and cooling units record a change in composition in their late stages. The frequency of such occurrences cannot be determined from published information; however, where such changes occur in young and fresh rocks, they offer an unprecedented approach to the study of problems of geochemical equilibrium in silicic magma chambers and will perhaps provide new information on the behavior of magmas. Time intervals, with their attendant possible changes, are drastically reduced or eliminated, a condition not shared by normal volcanic or intrusive sequences.

Origin of the Magmas

The evidence suggests that welded ash flows are not unique to any type of vent, source area, or composition of magma. Nevertheless they appear to be formed largely from fissures, are seemingly more common among large-volume deposits associated with subsidence structures, and more abundant among silicic magmas.

The large-volume deposits are confined to continental mountain belts or to wide island-arc systems, or in short to those environments that seem most likely to produce large volumes of granitic magma. This brings us directly to the contrasting concepts of the separateness or unity of volcanic and plutonic associations discussed by Kennedy and Anderson (1938).

Deposits of small volume, whatever their ultimate origin, have had an immediate origin within a volcanic dome or cone. Larger volumes related to caldera collapse were almost surely derived from shallow magma reservoirs having areal dimensions at least as large as the calderas, which in order 5 of Figure 3 range up to at least 20 square miles (Crater Lake). At depth these sites would logically be occupied by small plutons, and most are associated on the surface with more mafic volcanic rocks both older and younger than the ash-flow eruptions.

Some of the source structures associated with fields of order 5, 6, and probably 7 (Fig. 3) are true cauldron-subsidence structures, complete with ring volcanoes and a central stock; the latter is inferred from an observable uplifted central dome of pre-subsidence rocks. Oftedahl (1957) has recently shown that the volcanic rocks of the ring structures near Oslo, Norway, long thought to be lava flows and intrusive rocks, are really welded tuffs and related effusive rocks. Buddington (1959) has recently reviewed the granite problem and has called attention to the clear-cut, volcanic-plutonic relations among the epizonal plutons. Buddington (1959, p. 680) cites Billings (1943, p. 134) as having found that 11 out of 30 ring complexes reported at the time of his survey contain volcanic rocks. Probably all of these should be re-examined for welded tuffs.

The ring complexes, then, offer the best proof of a direct relationship between extrusive and plutonic rocks. Within some of these structures, ash-flow eruptions must have come directly from magma bodies that later congealed as plutons. The ring-dike complexes are commonly grouped in such a way as to suggest that they are only the upper part of a large subjacent complex (Buddington, 1959, p. 680-690; Jacobson, MacLeod, and Black, 1958).

The calderas associated with deposits of order 6 (Fig. 3) have areas of the order of 50 to 150 square miles; presumably the underlying magma bodies are at least as large and probably larger. Many ring structures are of comparable size although some ring-dike complexes are notably larger. Billings (1928, p. 86) says that the White Mountain New Hampshire "batholith" and associated volcanic rocks cover an area of 680 square miles.

Deposits of order 7 (Fig. 3) were almost necessarily derived from even larger magma bodies. The Toba volcano-tectonic depression occupies an area of approximately 1200 square miles which suggests a magma body of at least 60 miles long by about 20 miles wide or equal to the dimensions of the structure. Van Bemmelen (1939, p. 130) states that the estimated volume of pyroclastic rocks erupted approximates the volume of the Toba subsidence.

Buddington (1959, p. 681) has calculated that the 2300 cubic miles of rhyolitic volcanic rocks belonging to the Potosi volcanic series of the San Juan Mountains of Colorado (Larsen and Cross, 1956, p. 94) are equivalent to a "granite batholith" 230 square miles in area and 10 miles deep.

Certainly volcanic eruptions have produced volumes of pyroclastic rocks, principally in the form of ash flows, of enormous proportions, over a short period of time. It is inferred that greater volumes of magma were not erupted, but remained behind to congeal as large plutons. The present evidence, from known volcanic fields and from plutonic complexes that contain subsided blocks of volcanic rocks, indicates

immediate sources of many ash-flow
small to large granitic to dioritic
s; they are not, however, directly
to the deeper-seated great batholithic
s. Nevertheless the tectonic settings
mal grouping of some ash-flow fields
common origins from deeper-seated

ering now the immense deposits of
e those of the Basin and Range prov-
western United States, perhaps the
t question is whether or not the ash-
ls truly represent the magmas from
ey were immediately derived. In other
re the rhyolite ash-flow fields derived
nite magma or do they represent only
erentiated part of bodies of quartz
te or granodiorite? If they represent
differentiated part, are they all or
t of that fraction? At Crater Lake the
shows that an ash-flow eruption can
e entire silicic differentiate, at least on
scale. Could this not also happen on a
le? Quartz latite and rhyodacite ash-
ets are common, in addition to the
ash flows, throughout the Basin and
province. Are these separate entities
her source areas or are they related
lly to the rhyolites, perhaps in a
tic succession? The answers to these
s may have real significance to students
eposits. It is suggested that the answers
found by careful studies of ash-flow
ons from common source areas.

Geochemistry

Valley of Ten Thousand Smokes

studies of Shipley (1920), Sayre and
rger (1919), Allen and Zies (1923),
s (1924; 1929) in the Valley of Ten
nd Smokes contain nearly all the known
ative information on the geochemistry
lows. The essentials of these studies are
ll known and include the tremendous
of chlorine and fluorine given off by
aroles; the transport in the vapor phase
ge number of metallic elements and their
ion in sublimate minerals around the
of fumaroles and in fissures; the detec-
most of these same metallic elements in
ltered glassy pumice; and their release
e pumice by attack of steam and acid
The reader is referred to Zies's (1924;
papers for details. These studies were
the finest of their kind, and their importance to students of ore deposits is well recognized. Especially important is the positive evidence for low-concentration, vapor-phase transport of metallic elements from seemingly ordinary magmas. Unfortunately, for students of pure magma chemistry, these deposits are formed from a mixed magma of andesite and rhyolite (Fenner, 1923, p. 38; Williams, Curtis and Juhle, 1956, p. 129).

The controversy over the source for the fumaroles has not yet been resolved. Griggs (1918, p. 97), Fenner (1923, p. 43), Allen and Zies (1923, p. 95), and Zies (1929, p. 4) have debated this point; although they recognize that some of the smaller fumaroles may have originated in the ash flow itself, they concluded that most fumaroles had a deeper-seated source.

Examination of the interiors of dissected prehistoric ash-flow deposits indicate that during cooling of many deposits vapor-phase activity was common. Moreover, a large proportion of ash flows, in particular those that crystallized during cooling, gave off vapors at their surface for many years.

This geologic evidence supports the belief that the "sand flow" generated a large proportion of its own fumaroles with some help from surface waters converted into steam by contact with the hot ash. Indeed, Williams (1954, p. 58) says, "Fumarole cracks gradually disappear downward within the avalance deposits; hence the ore-minerals were sublimated by gases given off by the fragmental ejecta and not by a deeper body of magma." The data published by the early workers at the Valley of Ten Thousand Smokes, however, suggest that many of the fumaroles rising from the "sand flow" in the vicinity of Novarupta, Falling, Broken, and Cerberus mountains are related to, or contaminated by, a deeper source. Allen and Zies (1923, p. 105) say, "The hottest areas (in 1918) are in the central part of the main Valley opposite Knife Creek Valley, in the Novarupta Basin, in Broken Mountain Valley and at a few points at either end of Knife Creek Valley. They all fall in a nearly circular but not continuous zone, with a salient extending out from Broken Mountain into the middle Valley." All the incrustations analyzed by Zies (1929, p. 41) containing more than 0.1 per cent boron were found in this same area, and fumarolic activity persisted here locally at least as late as 1952 (Muller and others, 1954, p. 66).

Lovering (1957, p. 1587–1588) has discussed the evidence (from the earlier papers of Shipley, 1920; Allen and Zies, 1923; and Zies, 1929) bearing on the geographic control of sulfur-acid

gases and carbon dioxide and concludes that these too existed in higher concentrations in the same general area mentioned above. These facts indicate that not all of the "Ten Thousand Smokes" were from the "sand flow", and we may infer that an area of about a 3- or 4-mile radius centering on Novarupta was subject, in addition to "sand-flow" gases, to gases from a source beneath the ash flow. Contamination of ash-flow fumaroles farther down the valley by ground-water transport of the deeper-seated materials seems a distinct possibility.

On the other hand, Lovering's (1957, p. 1587) conclusion that some source of acid gas was tapped in addition to that originally "imprisoned" in the ash flow seems based, in part, on the assumption that all the gas given off by the ash flow itself was present in void space at the time of emplacement of the ash. A more voluminous source of HF and HCl must have been the gas in solution in the glass fraction of the ash flow—conservatively, about 80 per cent of the solid material of the flow. A large proportion of the HF and HCl may have been released on crystallization of the glass. Some crystallization had taken place by 1919 (Fenner, 1937, p. 236). We may presume that crystallization was continuing in 1919. It may well be that this was the major source of the HCl and HF reported by Allen and Zies (1923, p. 143) and by Zies (1929, p. 61–68); it could have exceeded by several or many times the *volume* of free gas that could be entrapped in the voids at the high temperature of emplacement of the ash flow.

Most of the gas released during initial vesiculation of the magma was certainly lost before the ash flow formed, and most of the rest was lost before final emplacement or during or shortly after the initial stages of compaction and welding, *before crystallization began*. Great quantities of the juvenile gases coming from the "sand flow" itself, 5–6 years after the eruption were probably being released by crystallization of the glass and had little physical relation to the entrapped gas released by vesiculation.

The rate of crystallization in volcanic glass is not well known, but temperature, composition, volatile content, and time are important variables. Some ash-flow cooling units 250–300 feet thick show marked but not dense welding and have remained vitric after cooling. Others may be only 50 feet thick, yet show dense welding and have a persistent crystalline zone. Clearly the latter had a shorter cooling history than the former in spite of its higher initial temperature. The "sand flow" over most of its area seems to fit somewhere between the above examples both in thickness and in crystallinity, as well as presumably, in time for cooling. The maximum thickness of the "sand flow" is not known, but Zies (1929, p. 4) states that it is at least 100 feet thick, and this was the thickness used for volume calculation. At least mild welding and crystallization are indicated from Fenner's (1923; 1937, p. 236) allusions to indurated material, reactions with inclusions, concavity of the surface of the flow, presence of tridymite and sanidine in some of the materials, and from illustrations in Griggs's (1922) and Fenner's (1923) papers, especially those showing crude columnar structure and fallen blocks of coherent material.

In essence, the evidence forcefully implies that the time of release of gas by crystallization varies considerably in different deposits and even in the same deposit where cooling gradients differ. The "sand flow" probably underwent a period of dormancy, for release of juvenile gas, between the time of welding and compaction when most of the trapped gas was released and the time the glass began to crystallize. This time could have been 2–3 years during which fumarolic activity, if any, may have been largely supported by reheated ground water. The validity of this reasoning depends on whether or not the glass of the "sand flow" could remain oversaturated in volatiles from the time of its eruption and throughout the period ending with crystallization. In all probability it could not. However, Kozu (1934, p. 164–165) reports that, of the two types of pumice from the 1929 eruption of Komagatake, the "pumice-flow" type retained more HCl and gave it off at lower temperature (when reheated) than the air-fall type did. These specimens presumably were collected within the first year after the eruption.

The "sand flow" was formed in 1912, discovered in 1915, and the first studies of temperature and fumarolic products were during the period 1917–1919.

If the line of reasoning leading to the suggestion of a period of "dormancy" during the early years of the "sand flow" has merit, then extrapolation of amounts of volatiles given off, beyond the period of observation of the fumaroles, must be severely restricted.

Ancient Deposits

Many of us have been fascinated with the thought of finding fumarolic mineral deposits

those described from the "sand flow", ; ash-flow deposits. Traces of former activity in the tops of some sheets 1952, p. 1337–1338 and oral com- n; Gilbert, 1938, p. 1851–1854; Wil- 12, p. 86–87; 1952, p. 156) and thick vapor-phase crystallization in others eem likely that many ancient sheets "sand flow" had parallel histories. many ancient deposits show evidence had far more intense vapor-phase han did the "sand flow."

929, p. 18–19) has emphasized the l nature of the "sand-flow" sublimate nd has stressed the importance of emperature and steam dynamics. important is the absence of magne- other minerals when the temperature arole falls to the point where steam . The minerals are then dissolved by cids and water. The persistence of osits can probably be ruled out for oling units on the assumption that uld have conformed closely to the et by the "sand flow."

und cooling units in ancient deposits non. This leads us to wonder what appen to the fumaroles and their in a sheet at the stage of cooling of d flow" during the period 1917–1919 r ash flow were emplaced on top of it. much would depend on the charac- of the second flow, which, if it were hot kly welded, might effectively seal in roles in the lower flow. Ultimately, ing factors would probably be ground d permeability. The suggestion is at these compound cooling units that dence of marked breaks in their cooling hould be examined very carefully for maroles and traces of their former

chemical analyses of rocks now known ash-flow origin have been published. ord compositions ranging from basalt te and trachyte, but show no notable es as a group from normal lavas of compositions. The same statement in so far as is known at present, to ments.

and Goldich (1956, p. 168–169) found "salmon sillar" from the Arequipa Peru, contained small amounts of alts (chloride and sulfate), and halite ermined by X ray. They attributed introduction by "ground water, which saline owing to leaching of volcanic deposits." This study suggests examination of vapor-phase zones in ancient deposits for water soluble salts, if suitable deposits could be found, located above present and past water tables.

Systematic geochemical studies of welded ash flows are needed. We are now in a position to make such studies of *limited* scope. They should be made, in the beginning, on the youngest possible fresh rocks. Probably some sheets will be essentially homogeneous chemically, and others not. We need to know the differences and their orders of magnitude.

Geochemical studies must consider the degrees of welding and types and degrees of crystallization. Major and minor elements should be determined in relation to the zonation in simple cooling units, preferably in single flows. Great care must be taken to evaluate contamination by inclusions, and in the selection of suitable samples. J. H. Mackin (oral communication, 1957) has arrived at similar ideas based on his preliminary work in southeastern Nevada.

Concluding Remarks

The problem of ash flows is in a formative stage, and a great deal of study is needed, especially to supply quantitative data. Rocks and rock bodies of ash-flow origin are now known to be so common that their recognition is no longer surprising, as it was only a decade ago. It no longer seems necessary to recapitulate the arguments or early history of development of concepts.

The importance now of recognizing these rocks, aside from pure knowledge, is because they are useful tools for the understanding of other geologic processes. Here their usefulness may be many fold, but much will depend on the accumulation of quantitative information from entire pyroclastic fields, composite sheets, or cooling units.

The important use of widespread ash-flow deposits for correlation of stratigraphic sequences, although recognized 20 years ago by Anderson and Russell (1939), is now being more fully explored and holds great promise. Many, if not all, ash-flows fields are associated with extensive air-fall beds. In and adjacent to the post-Cretaceous continental orogenic systems, we should be able to establish eventually a "tephrachronology" for the entire Cenozoic that may transcend anything envisioned today.

Detailed studies of the cooling characteristics of simple ash-flow sheets and the application

of the information to more complex sheets and to entire fields could eventually lead to concepts of eruption intervals, depositional time spans of certain rock units, and other time concepts that we do not now have.

Some of these great sheets surely represent magmas which, if intrusive, would have produced, or caused production of certain types of ore deposits. They, together with associated air-fall pyroclastic rocks, represent perhaps the closest possible approach to arrested equilibria in silicate melts that it is possible to attain in nature. In effect they may represent a quenched inverted sample of differentiating silicate magma throughout a depth of at least the upper several thousand feet in many magma chambers. To be sure most of their volatile constituents have been lost, especially those first released, but others are retained in glass, or their passage is recorded in crystallized welded tuffs. The phenocrysts remain, however, and detailed geochemical and petrologic studies of them and their relationship to their glass matrix should be made. The significance of such studies will depend on the extent to which they are guided by careful investigations of the pyroclastic fields in their entirety and should eventually encompass a variety of petrographic provinces, compositions, and fields of different volumes. Presumably the most useful data will come from those materials that represent the widest variation in composition within a single eruption cycle. All these pyroclastic deposits probably record some kind of differentiation, ranging from the extremes of a basalt-rhyolite relationship to changes in the crystal-liquid chemistry of crystallizing granite magmas.

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