Zones and Zonal Variations in Welded Ash Flows

GEOLOGICAL SURVEY PROFESSIONAL PAPER 354-F

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By ROBERT L. SMITH

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 354-F

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

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1960

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

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ABSTRACT

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

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

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

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

Three principal types of crystallization that take place during the cooling history are recognized. These in order of frequency of occurrence, are devitrification, vapor-phase crystallization, and granophyric crystallization. The *zone of devitrification* is common to most crystallized welded tuffs and frequently occupies most of the zones of dense welding and partial welding. The *zone of vapor-phase crystallization*, where present, occupies the porous parts of the welded tuff sheets and reaches its maximum development in the upper zone of partial welding where it overlaps the zone of devitrification. The *zone of granophyric crystallization* is probably confined to cooling units several hundreds of feet thick where it will divide the devitrified zone into upper and lower parts. Fumarolic alteration may be found in the upper zone of no welding.

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

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

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

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

INTRODUCTION

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

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

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

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

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

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

ACKNOWLEDGMENTS

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

ERUPTION AND EMPLACEMENT

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

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

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

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

WELDING

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

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

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

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

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

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

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

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

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

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

CRYSTALLIZATION

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

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

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

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

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

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

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

EXPLANATION OF PLATE 21

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

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

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

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

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

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

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

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

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

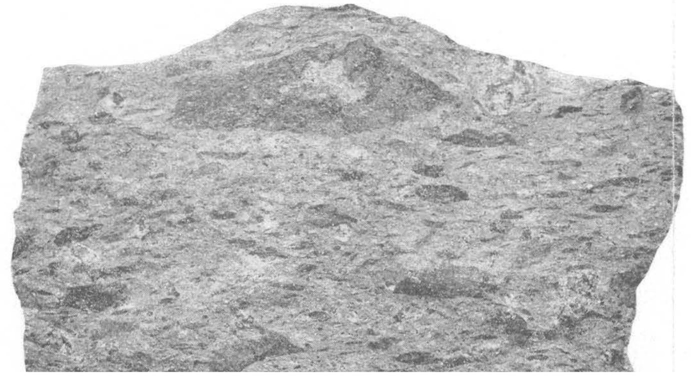
H. Vapor-phase zone (upper zone of partial welding). Compaction foliation well developed. Pumice-tube structure not as well preserved in this plane, but very obvious in the plane of flattening. Approximate crystalline equivalent to *C*.

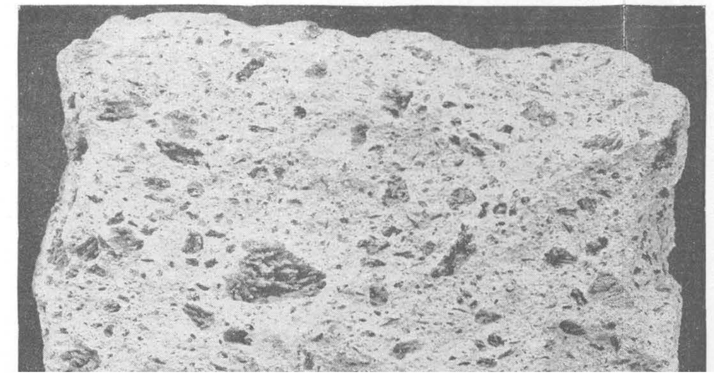
I. Devitrified zone (zone of dense welding). Some collapsed pumice fragments visible. In thin section this specimen shows coarse axiolitic devitrification.

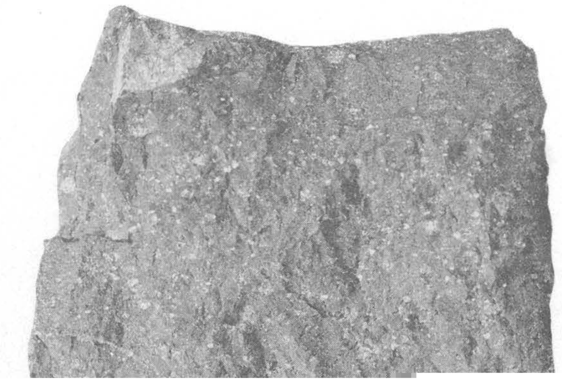
J. Devitrified zone near base (zone of dense welding). Fine-grained devitrification of a dense black glass. Only faint traces of original pyroclastic character preserved in hand specimen. Perfect preservation of shards and flattened pumice fragments in thin section. Crystalline equivalent to *F*. Matahina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

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

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







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

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

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

THE ZONES

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

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

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

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

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

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

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

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

ZONE OF NO WELDING

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

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

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

ZONE OF PARTIAL WELDING

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

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

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

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

ZONE OF DENSE WELDING

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

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

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

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

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

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

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

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

ZONES OF CRYSTALLIZATION

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

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

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

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

Some of the features that may mark this transition are: (a) The upward appearance of vapor-phase minerals; (b) a visible upward increase in porosity; (c) a downward change in color or shading of color from light to dark; (d) a downward change from coarse to fine joint spacing; and (e) the zone of dense welding is usually a better cliff former in crystalline tuffs.

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

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

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

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

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

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

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

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

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

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

COOLING UNIT

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

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

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

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

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

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

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

COMPOSITE SHEET

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

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

INFLUENCE OF BURIED TOPOGRAPHY

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

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

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

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

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

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