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The Bandelier Tuff: A Study of Ash-flow Eruption Cycles from Zoned Magma Chambers * [1]

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U. S. Geological Survey, Washington, D. C.

Introduction

The Bandelier Tuff (H. T. U. SMITH, 1938; GRIGGS, 1964; ROSS, SMITH, BAILEY, 1961), Jemez Mountains of northern New Mexico, U.S.A. (Fig. 1), is a Pleistocene rhyolitic ash-flow formation consisting of two major members. In this preliminary paper the two major members are designated informally as the upper member of the Bandelier and the lower member of the Bandelier. Formal subdivision is planned for a later paper. Each member is the product of a giant caldera-forming eruption: the eruption of the lower member of the Bandelier approximately 1.4 million years ago, was followed by subsidence in its source area to form the Toledo Caldera; the upper member of the Bandelier was erupted approximately 1.0 million years ago, and formed the Valles Caldera (SMITH, BAILEY and ROSS, 1961; K/Ar ages from G. B. DALRYMPLE, personal communication). The upper and lower members of the Bandelier thus form two cycles of ash-flow eruption and caldera formation that together are the culmination of a long history of basaltic and andesitic to quartz-latitic and rhyolitic volcanism in the Jemez Mountains.

Because of the similarity between the upper and lower members of the Bandelier, both in physical and chemical properties, and because space does not permit more than a preliminary account, details of the upper Bandelier only are described here. The following pages are a brief summary of the distribution, stratigraphy, and preliminary mineralogy and chemistry of the upper member of the Ban-

* Publication authorized by the Director, U. S. Geological Survey.
[1] Paper read at the IAV International Symposium on Volcanology (New Zealand), scientific session of Nov. 25, 1965.

delier. The lower member of the Bandelier will be referred to for significant comparison.

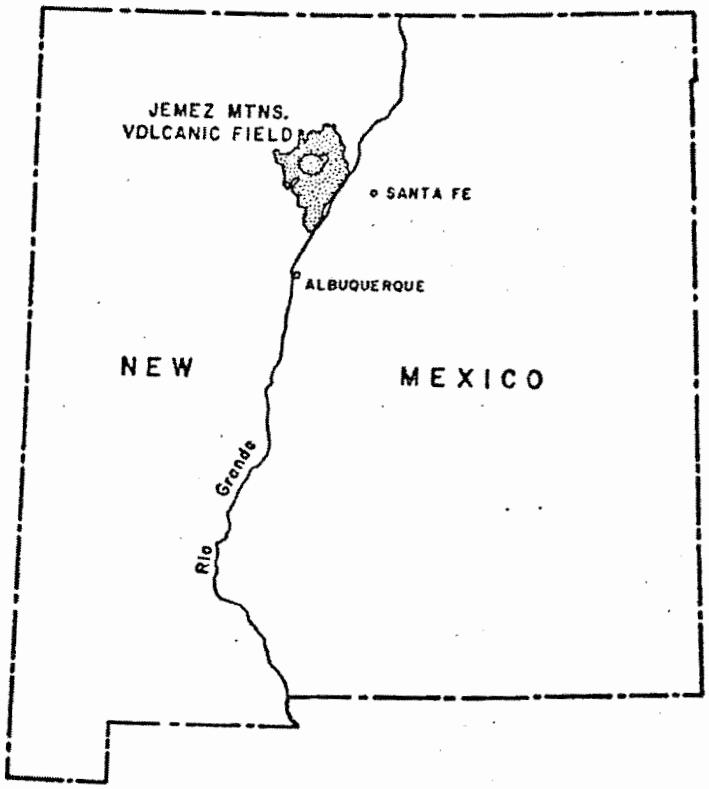

FIG. 1 - Index map of New Mexico showing location of Jemez Mountains volcanic field.

Distribution

The Bandelier Tuff forms broad plateaus that slope radially from the Jemez Mountains volcanic highland. The plateaus are dissected by numerous deep canyons radial to the Jemez Mountains, and these canyons provide many hundreds of miles of exposure of the Bandelier (Fig. 2). Figure 3 shows the physiography of the Jemez volcanic highland, the Valles Caldera, and the flanking plateaus of Bandelier Tuff. The total Jemez volcanic field has dimensions of about 60 miles north-south and about 40 miles east-west.

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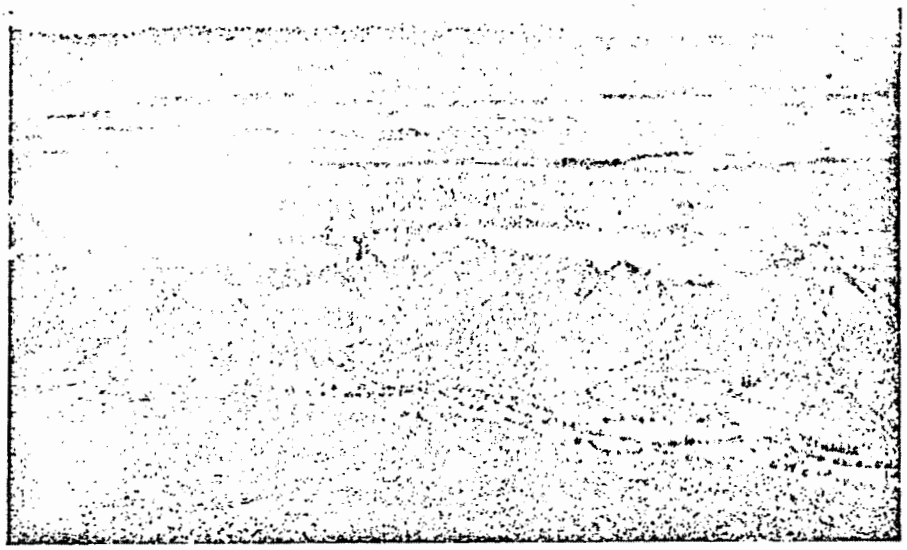

FIG. 2 - Aerial view of Bandelier Tuff cliffs on the west side of San Diego Canyon and the dissected surface of the Jemez Plateau, west side of the Jemez Mtns. (Nacimiento Mountains in distance). The lower two dark and light bands in the cliff constitute the lower member of Bandelier; uppermost dark and light bands constitute the upper member of Bandelier.

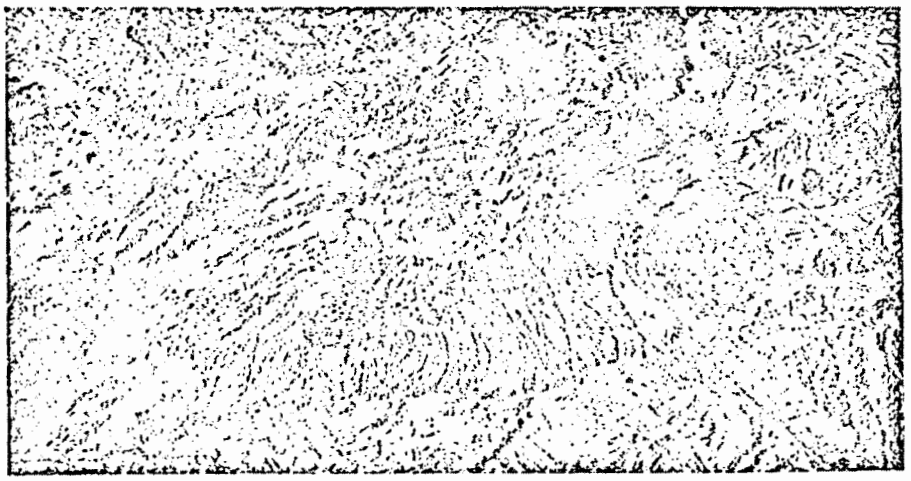

FIG. 3 - Photograph of a relief model of the Jemez Mountains area showing the Valles Caldera (center) and flanking plateaus of Bandelier Tuff. View as seen from the southeast.

The present outcrop area of the Bandelier ash-flow sheets is about 500 square miles. The upper member of the Bandelier formerly covered about 830 square miles (Fig. 4) and had a volume of about

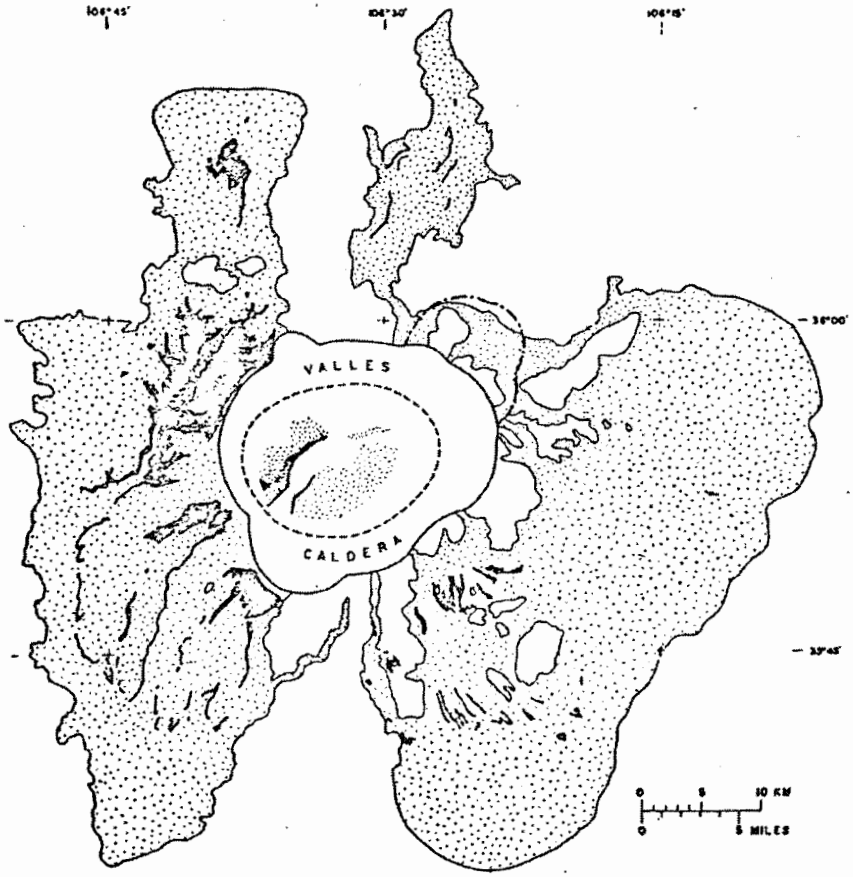

FIG. 4 - Distribution of Bandelier Tuff around the Valles Caldera (topographic rim, solid black line; ring fracture, dashed line) and Toledo Caldera (topographic rim, dash-dot line). Outcrop of lower member of the Bandelier, solid black. Maximum extent of upper member of the Bandelier, dotted.

50 cubic miles. The lower member of the Bandelier had approximately the same distribution and volume, but pre-upper Bandelier erosion has reduced its distribution, and burial by the upper member of the Bandelier restricts its present outcrop (Fig. 4).

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In the interval between the upper and lower Bandelier eruptions, the lower member of the Bandelier was extensively eroded and deeply incised by radial canyons. The upper member of the Bandelier was

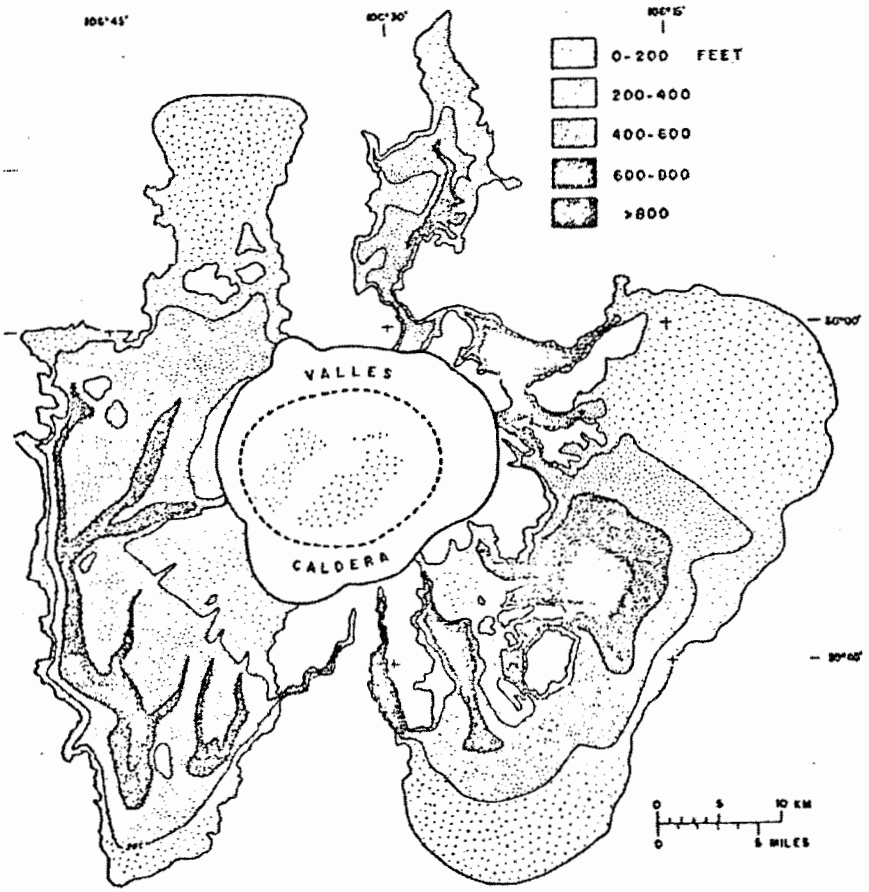


FIG. 5 - Isopach map of upper member of Bandelier Tuff.

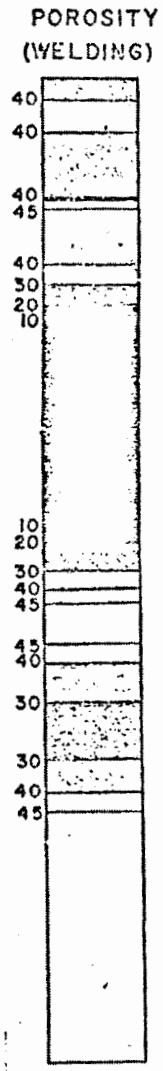
emplaced on the much dissected topography of the lower member and pre-Bandelier rocks. Simplified isopachs (Fig. 5) show the highly variable thickness of the upper Bandelier ash-flow sheet and emphasize the influence of topography in controlling thickness and distribution. Locally it is more than 800 feet thick, the greatest known thickness being in the Toledo Caldera basin.

The ash-flow eruptions of both the upper and lower members of the Bandelier were preceded by pumice falls and these deposits are nearly everywhere present beneath the ash-flow sheets.

Stratigraphy

The present study is based on observation and measurement of numerous detailed stratigraphic sections. All sections were hand leveled and all observable features recorded. The diagram of Figure 6 illustrates some of the features noted and serves to illustrate the basis for construction of Figures 7, 8, 11 and 12. Degree of welding was determined by porosity estimates every 5-10 feet. Kind and intensity of groundmass crystallization or absence of it were noted. Particularly significant were pumice block accumulations, crystal concentrations, and other features that mark partings between individual ash flows. « Fossil » fumarolic pipes were found to be valuable indicators of flow tops. Composition and size of lithic fragments; size and mineralogy of phenocrysts; size and texture of pumice blocks; color both on fresh and weathered surfaces; and joint, weathering, and erosion characteristics were recorded. All these features considered collectively provide valuable means of correlation over the entire Bandelier sheet. Typically no two sections are alike, and no single section is representative of the entire sheet. Sections were correlated by visual field relations, by best fit of observed features, and by contouring of lines of equal porosity (degree of welding).

Reversals in porosity trends in vertical sections, common in the Bandelier, indicate different *rates* of welding and reveal variations in emplacement temperatures of individual ash flows or groups of ash flows. In Figure 7 four simplified sections of the upper member of the Bandelier that span about 8 miles are joined by lines of equal porosity. The uppermost stratigraphic layers have been removed by erosion, and the principal field key to correlation is the position of the zone of maximum welding. Locally this zone is composed of at least six successive ash flows and can be traced for 12 miles in continuous outcrop. Figure 8, a greatly simplified cross section, spans a distance of 15 miles radially from the Valles Caldera and is constructed from 5 measured sections (4 of which are shown in Fig. 7) and inter-section inspection. The porosity contours, besides aiding in correlation of measured sections, show how welding decreases away



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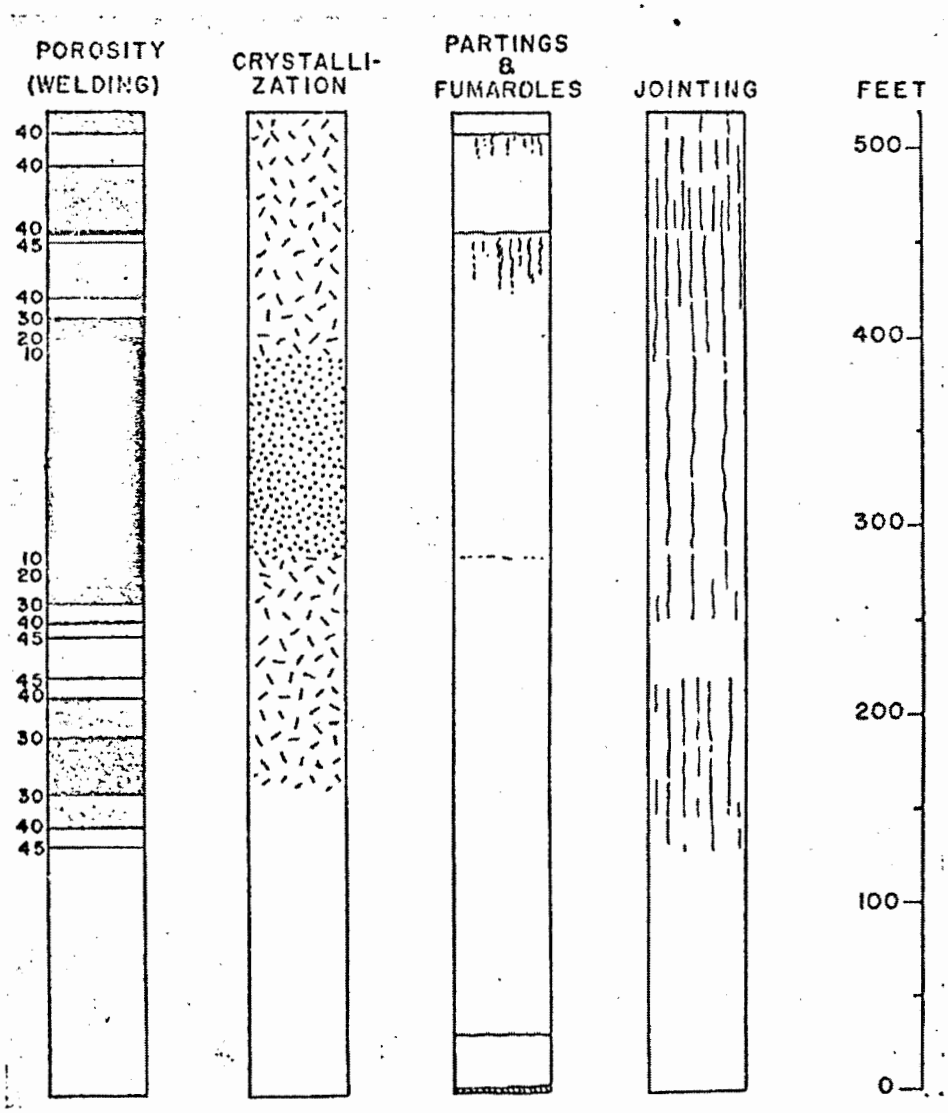

Fig. 6 - A sample stratigraphic section of the upper member of the Bandelier Tuff, showing recorded changes in degree of welding (percent porosity, shaded), crystallization, (vapor phase, dashed; devitrification, dotted) position of partings and fumaroles, and spacing of joints.

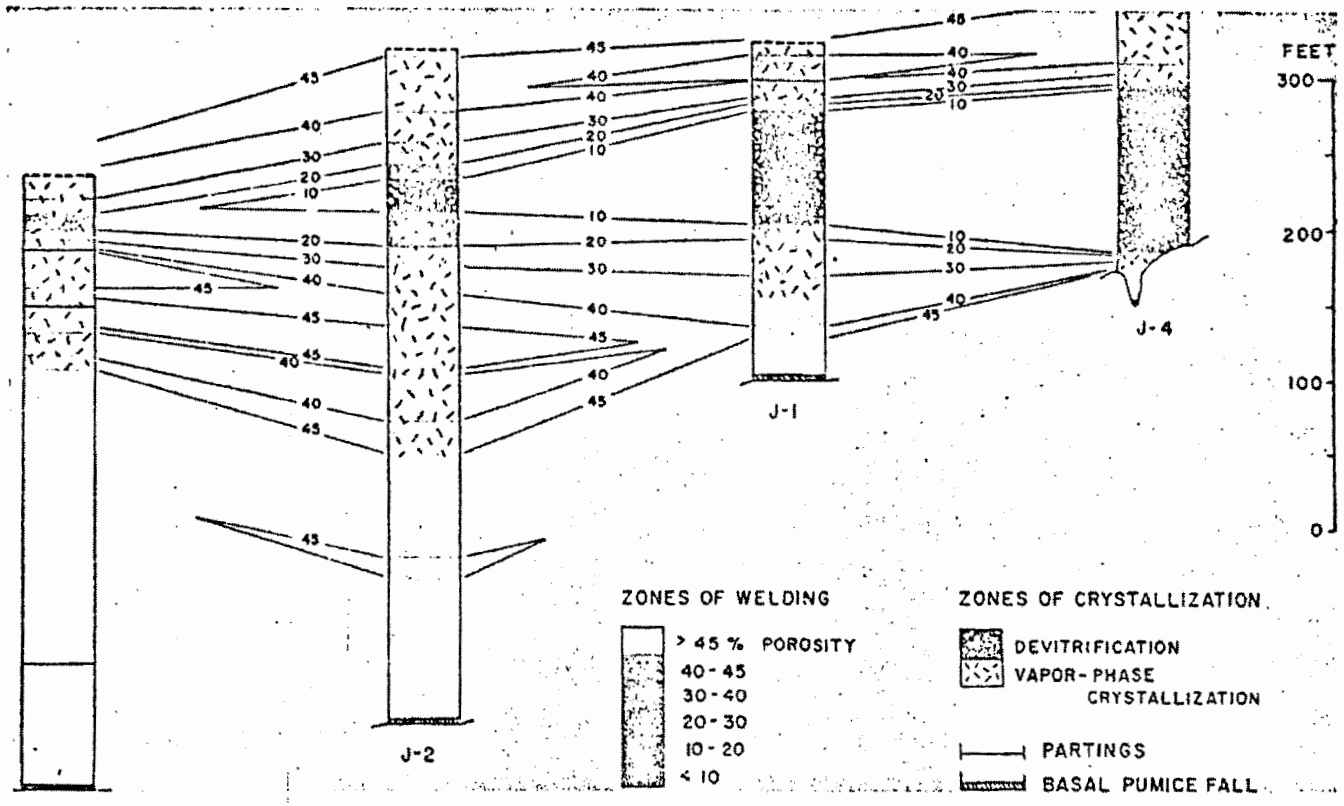

Fig. 7 - Correlation diagram of stratigraphic sections of upper member of the Bandelier Tuff in San Diego Canyon, Jemez Plateau, showing projected porosity contours and the relation of zones of crystallization to zones of welding.

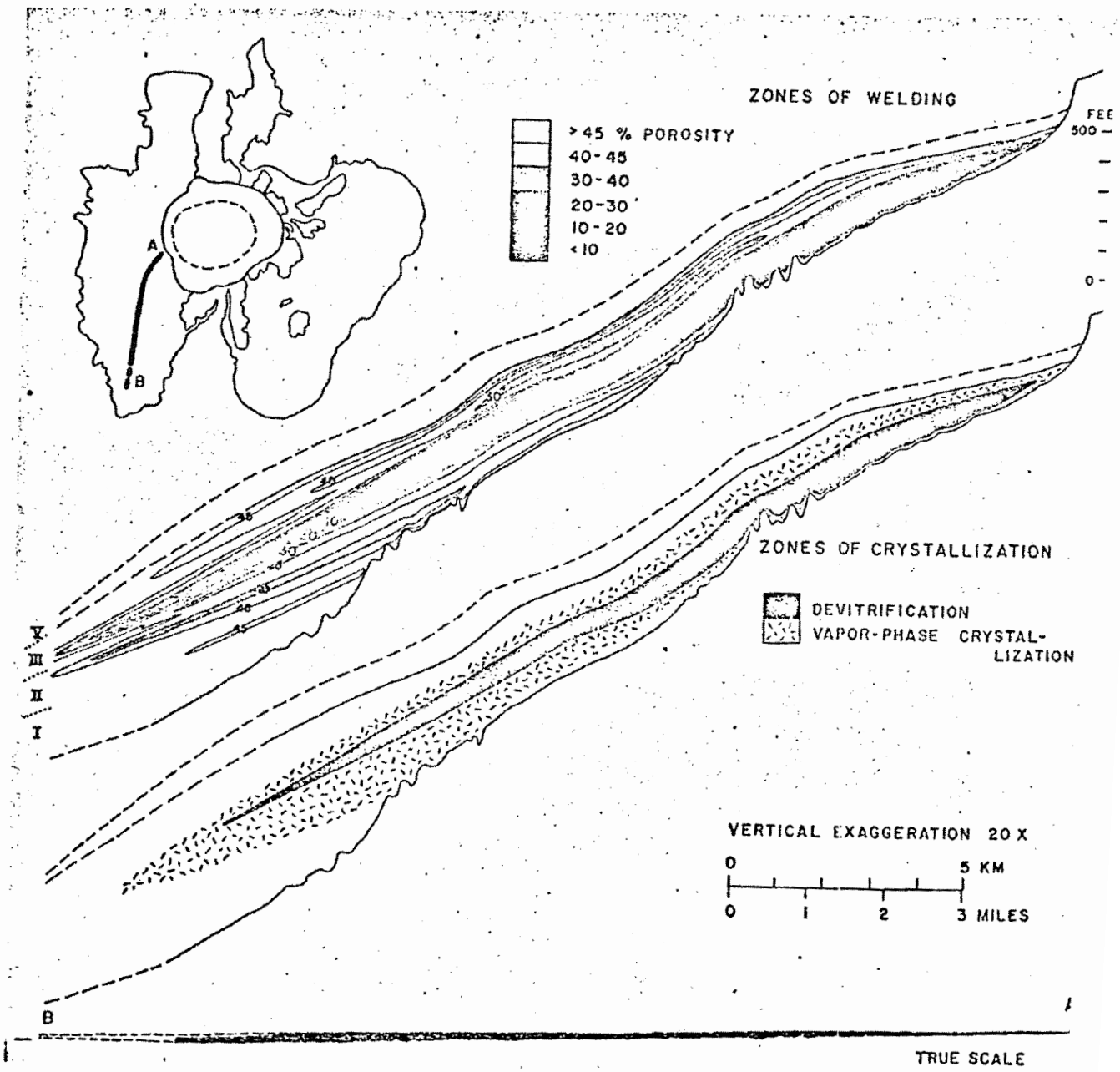

FIG. 8 - Cross section showing zones of welding and crystallization in the upper member of Bandelier Tuff in Sa Diego Canyon, Jemez Plateau. Roman numerals refer to stratigraphic subunits shown in Figure 9.

from the source area even though the total cooling unit thickens. This lateral decrease in welding is related to heat loss during emplacement of the ash flows. The heat loss toward the distal end of the sheet is also confirmed by the decrease in thickness of the zone of crystallization relative to the thickness of the cooling unit. This change in zone thickness is related to the total heat budget of the cooling unit rather than to individual ash flows as shown by the fact that the lower zone-boundary between crystalline and noncrystalline tuff steadily rises in the cooling unit toward its distal end and crosses partings between individual ash flows.

To understand the stratigraphy of either the upper or lower members of the Bandelier it is necessary to visualize the eruption and emplacement of the ash-flow materials from a volcanic highland onto a much dissected lowland. The early ash flows were confined to the valleys and basins, successive flows filled the valleys, and the later ash flows merged to form continuous sheets from which scattered mountain peaks protrude.

In general the thickest sections are most likely to reveal the earliest ash flows, although the location of lowland areas and the assymetrical distribution of successive flows from the highland source vents combine to complicate the flow sequences and create gaps in any given section where certain flow units or their correlatives are missing.

Because of many factors, it is impossible or impractical to correlate individual ash flows over long distances Consequently other means were devised to frame a useful stratigraphy.

Correlation of nearly 100 detailed stratigraphic sections has permitted recognition of five stratigraphic subunits within the upper member of the Bandelier (Fig. 9). These subunits are made up of groups of ash flows and are identified by their relative emplacement-temperature characteristics and by their mineralogy. The subunits are not everywhere sharply defined but they represent stratigraphic zones that can be correlated over the entire outcrop area. The pumice fall layer is present at the base of the upper Bandelier except where the underlying topography was too steep for lodgment. Pumice fall not in unit I

Subunits I, II, and III contain prominent phenocrysts of quartz and sodic sanidine and are recognizable in the field as a progressive temperature sequence. Subunit I is composed of ash flows that rarely show welding or groundmass crystallization even where overlain by several hundred feet of section. This subunit occurs in lower parts I = Unit 1g

of all major valleys filled by the upper member of the Bandelier. Subunit II is composed of ash flows that typically show partial welding and vapor-phase crystallization, but no dense welding. Subunit III contains a densely welded and devitrified zone over a large portion of the outcrop area, although in its distal portions, where it is thin, or where it has chilled against buried topographic highs, it physically resembles subunits I or II. Subunit V, the topmost unit, is characterized by large zoned phenocrysts of anorthoclase rather than of sodic sanidine.

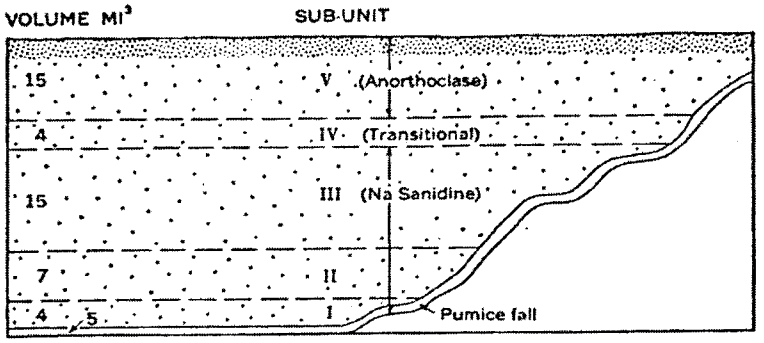

FIG. 9 - Schematic stratigraphic diagram of the upper member of the Bandelier Tuff.

Subunit IV, designated the « transition unit », is most critical. It is a zone of mixing where anorthoclase and hypersthene-bearing pumice and sanidine and fayalite-bearing pumice occur together. It is also a zone of abrupt upward decrease in modal quartz. Subunit IV is not equally distributed and in some areas is not present or is not recognized. Four of the subunits are represented in the exposure shown in Figure 10. Subunit V has been removed by erosion at this locality.

Topographic restriction of subunits I and II, and the wide distribution of subunit III are well illustrated by the cross section of Figure 11. As a consequence of differential compaction of subunits II and III and the limited distribution of subunit IV, subunit V rests directly on subunit III at the eastern edge of the cross section. To the west, ash flows of subunit IV occur in normal succession between subunits III and V (Fig. 11).

The increasing temperature sequence of subunits I-III is well illustrated by Figure 11. The lowermost portions of the cooling unit

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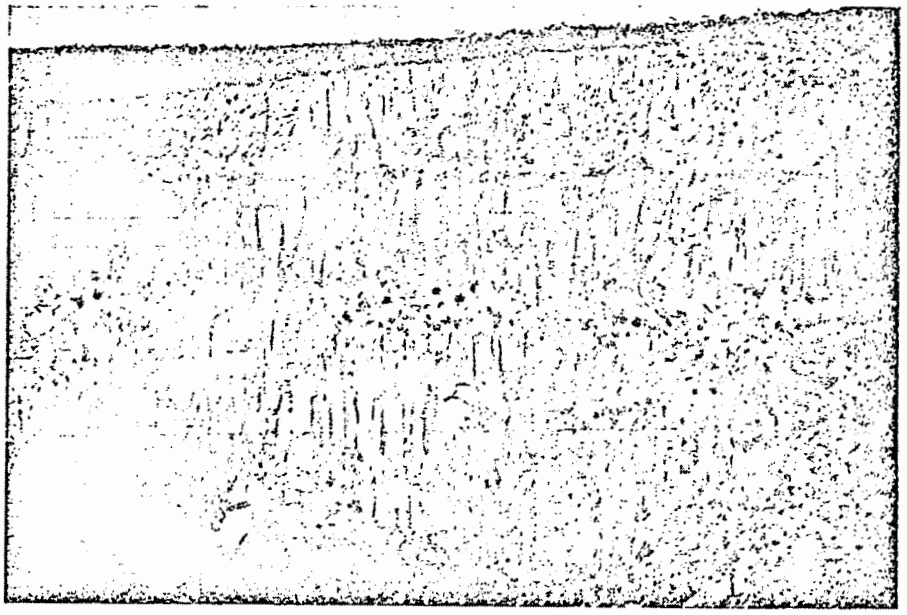

FIG. 10 - A 550-foot cliff in upper member of the Bandelier Tuff, Canon de la Canada, Jemez Plateau. Dark band in middle of cliff is subunit III; subunit IV is above, and I and II below.

are nonwelded and noncrystalline and all sections show an upward increase in degree of welding (as shown by decrease in porosity) into subunit III. This sequence is the reverse of that in a simple cooling unit emplaced at uniform temperature (SMITH, 1960). Reversals in porosity (welding) vertically in subunit II show the variability of emplacement temperature in successive flows.

Figure 12 shows a cross section that is closely representative of the total upper Bandelier sheet. All five subunits are present. Complications induced by underlying topography are shown by the abrupt appearance in subunit III of a thick zone of dense welding, and the absence of the same zone upslope as a result of the chilling effects of concealed topographic highs on the upslope portion of the subunit. The cross section of Figure 12 also confirms the emplacement temperature gradient previously discussed and illustrated by Figure 11.

Near the top of subunit III and in subunits IV and V the recognizable ash flows are thinner than those lower in the cooling unit, and the partings between the ash flows are more distinct. Zones of dense welding, separated by steep porosity gradients (Fig. 12) and by local vitric zones along partings, indicate cooling breaks of greater frequency and longer duration than observed in the lower part of subunit III and below. The thin zones of dense welding, occurring as they do near the top of the cooling unit, also indicate a continuation (with some reversals) of the trend toward higher temperature of successive ash flows shown more clearly by subunits I-III.

Preliminary Mineralogy

The mineralogical studies of the upper member of the Bandelier are incomplete, yet sufficiently advanced to illustrate significant magmatic trends. Figure 13 shows the general nature of the information stored in a composite section similar to that depicted by the western portion of the cross section of Figure 12. Alkali feldspar compositions (determined from a-parameters, derived by computer from X-ray data for heat-treated phenocrysts) are plotted against sample position in the section. The sanidine phenocrysts show a slight but significant trend toward a more sodic composition from the air-fall pumice base, through subunits I-IV. There is then a marked compositional change to strongly zoned anorthoclase in subunit V.

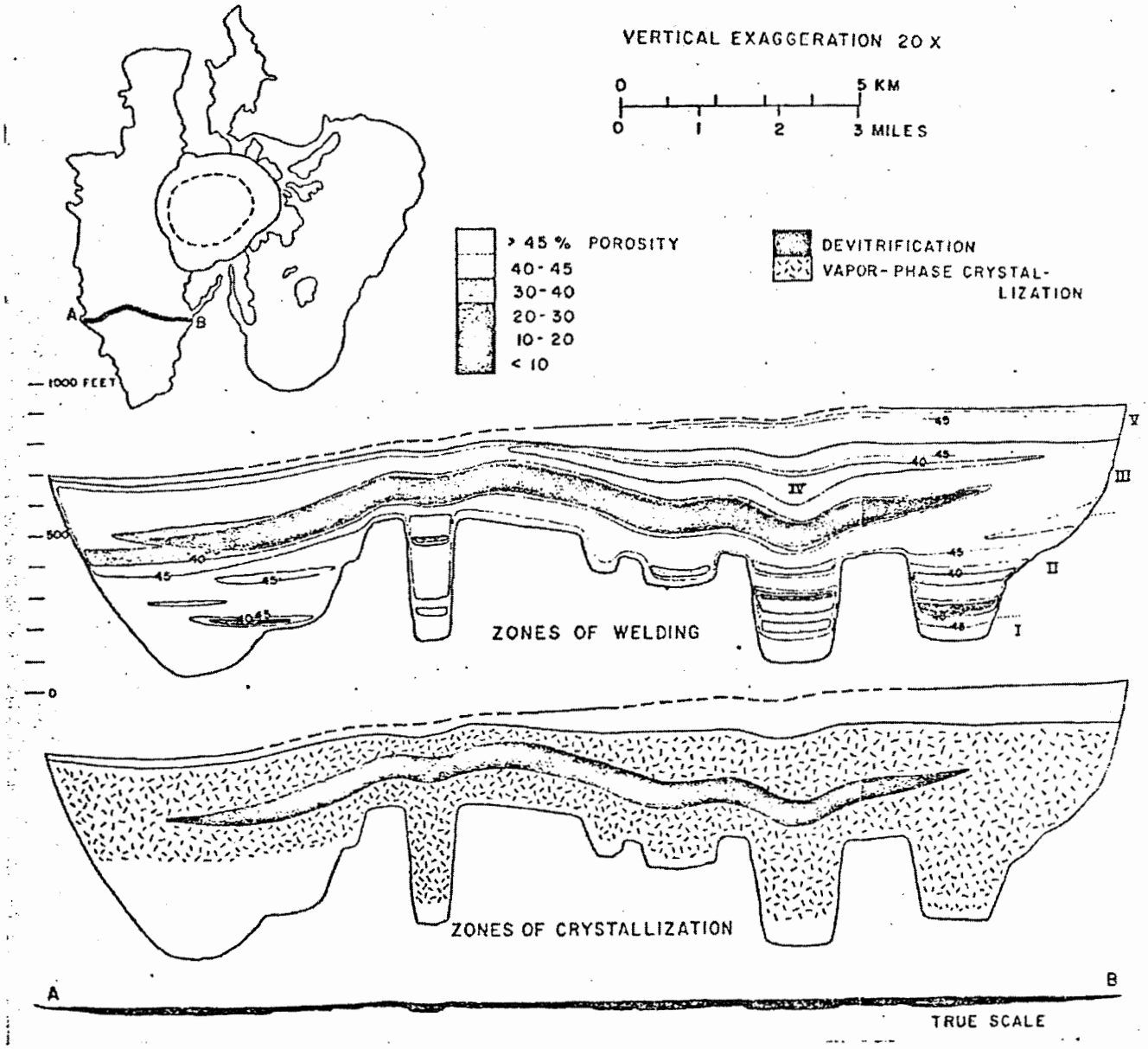

FIG. 11 - East-west cross section of upper member of Bandelier Tuff, Jemez Plateau, showing zones of welding and crystallization.

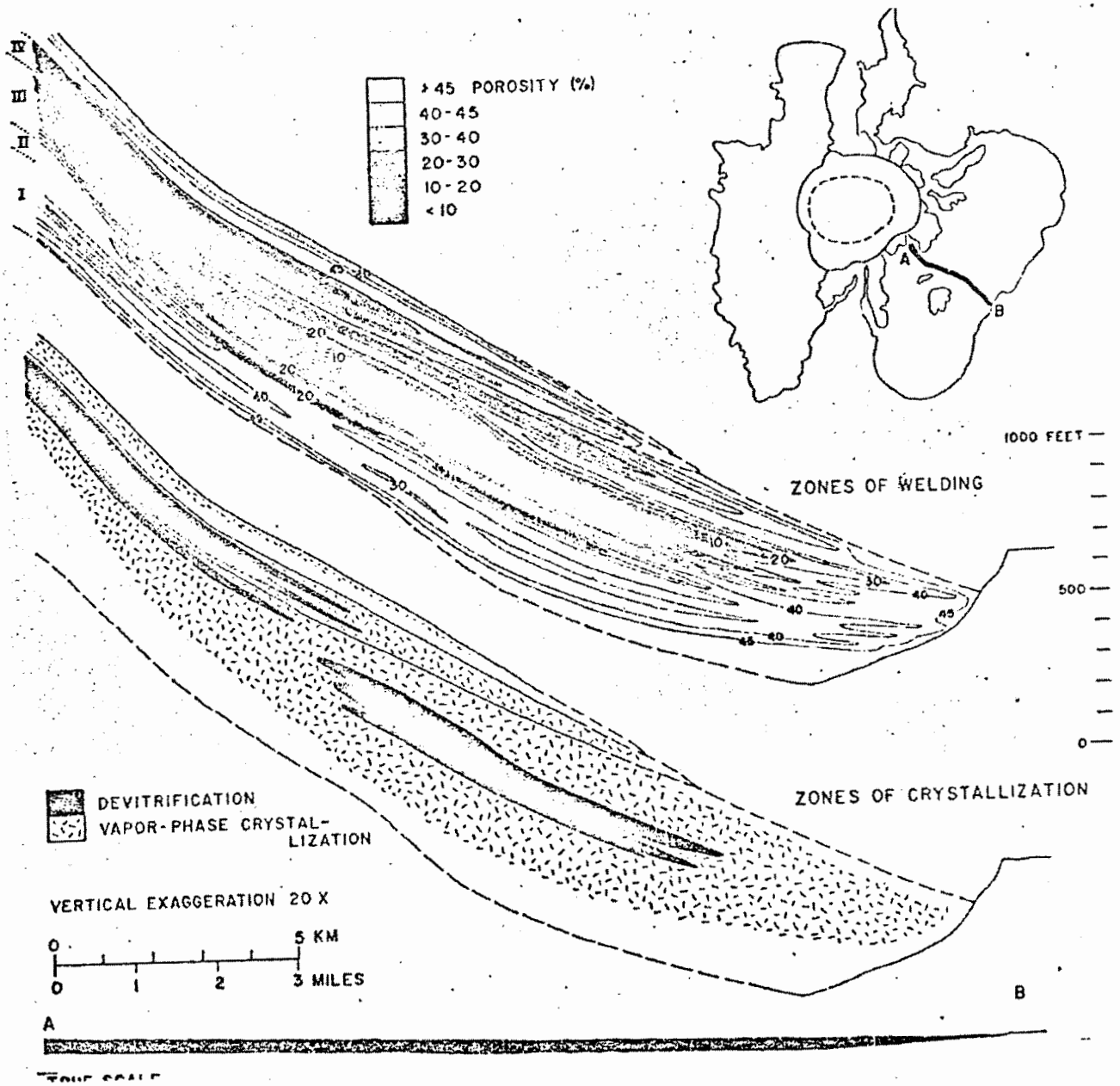

Fig. 12 - Cross section of upper member of the Bandelier Tuff, Frijoles Canyon, Pajarito Plateau, showing zones of welding and crystallization.

In subunit IV both anorthoclase and sanidine occur in bulk welded tuff, but they have not been found together in individual pumice blocks. Both the anorthoclase and the sanidine in subunit IV are variable in composition (Fig. 13), yet the sanidine is generally

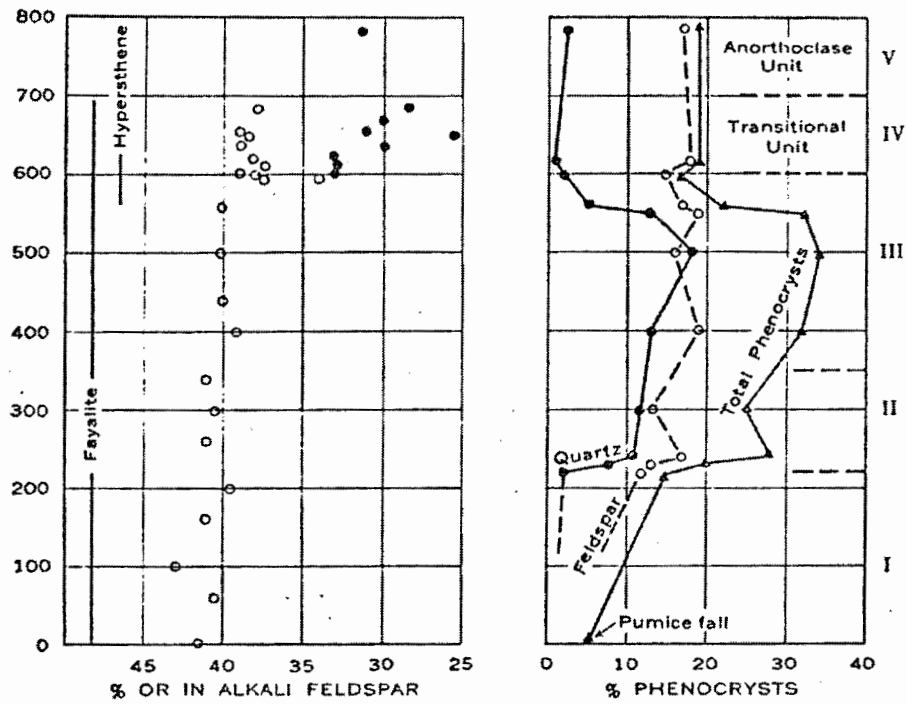

FIG. 13 - Modal percent phenocrysts and composition of alkali feldspar phenocrysts in an 800-foot section of upper member of Bandelier Tuff. Open circles, sodic sanidine (monoclinic); closed circles, anorthoclase (triclinic).

more sodic than in subunit III. The evidence from the feldspars indicates that subunit IV is a zone of mechanical mixing transitional between subunits III and V and suggests that some significant event occurred either in the magma chamber, in the conduits, or during the course of the eruption.

The distribution of fayalite and hypersthene offers additional information. Fayalite is restricted to sanidine-bearing pumice. Hypersthene, on the other hand, although ubiquitous in anorthoclase pumice, also occurs instead of fayalite in sanidine-bearing pumice, in some outcrops of subunit IV (and possibly III). Thus the change

from fayalite to hypersthene is independent of the change from sanidine to anorthoclase and provides critical evidence for continuity of crystallization, suggesting that the entire upper Bandelier was erupted from a single magma chamber.

Modal phenocryst content also shows significant change. The modal data (calculated porosity free) in Figure 13 were determined from single thin sections of bulk rock, hence are not rigorously representative. Nevertheless the changes are sufficiently large to be significant. Total phenocrysts increase from about 5 percent in the air-fall pumice to nearly 35 percent near the top of subunit III, where a marked decrease to about 20 percent occurs. The total-phenocryst curve is paralleled by the quartz curve, whereas the feldspar shows relatively steady increase with only minor variations. The sudden decrease in total phenocrysts at the top of subunit III is probably the result of preferential resorption of quartz, although both quartz and feldspar show resorption textures. This resorption may be most plausibly explained as due to the sudden release of pressure following removal of more than 20 cubic miles of overlying magma erupted as subunits I-III. Abundant field evidence indicates changes in the eruptive pattern beginning near the top of subunit III. Partings between ash flows become more distinct; wind-blown sand layers are more frequent and thicker, and fossil fumaroles are better developed. All these criteria indicate slightly longer time intervals between eruptive pulses.

In addition to these field features, to mineral mixing, and to phenocryst resorption at this level, an unusually high percentage of coarse lithic inclusions occurs at the top of subunit III. These inclusions may be the result of structural disruption during the early stages of collapse of the Valles Caldera.

The foregoing relationships suggest the following sequence of events:

1) Rapid eruption of some 20 cubic miles of magma with concomitant lowering of total pressure in the magma chamber.

2) Preliminary sagging or partial foundering of the cauldron block and wedging of the conduits, bringing the eruption to a temporary halt. The culminating ash flows of this phase (subunit III) carry abundant lithic inclusions derived from the conduit walls.

3) Disturbance of equilibrium due to lowered pressure causing resorption of quartz and feldspar in the magma chamber.

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4) Continued sporadic eruptions with short time breaks, allowing development of local disconformities, sandy partings, and fumaroles.

5) Reopening of conduits and eruption of remaining 10+ cubic miles of magma (subunit V).

6) Final collapse of the cauldron block into the magma chamber, thus forming the Valles Caldera.

Preliminary Chemistry

The 50 cubic miles of upper member of the Bandelier Tuff are equivalent to 35 cubic miles of magma. In Figure 14 total volumes of the subunits (Fig. 9) are reclaculated to volume percent of magma and inverted in sequence to show their relative positions in the magma chamber and their proportions as erupted. The data from four chemically analyzed feldspars agree remarkably well with X-ray data shown in Figure 13. The chemical differences between the feldspars from the pumice fall and from subunits II and III are small, but the trend is clearly confirmed by the CaO, Ba, and Sr determinations. The feldspars reveal a small but significant chemical gradient involving 35 cubic miles of silicate magma that is less than 25 percent crystallized.

As might be expected, the foregoing mineralogical changes reflect chemical changes within the upper member of the Bandelier. Chemical analyses of bulk rock samples of the upper member of the Bandelier show that SiO_2 decreases from about 77 percent in subunit III to about 72 percent in subunit V. (Chemical analyses of subunits I and II have not yet been made). Other differences, though small, are real as is shown by the trends in Figure 15. From subunit III to V there is a progressive decrease in total alkalies and a complimentary decrease in FeO relative to MgO. The lower member of the Bandelier (Fig. 15, open circles) has similar bulk chemical characteristics and shows a similar trend.

Additional chemical data are shown in Figure 16. The data on the distribution of U, Th, and Nb (GOTTFRIED, *et al.*, unpublished data) are most complete and the curves are based on a large number of bulk rock analyses averaged from several measured sections as well an analyses from selected samples. All three elements show a 3- to 4-fold decrease from the first to last erupted material. It is

important to note that these elements are not particularly sensitive to cooling history devitrification and vapor-phase crystallization or to the minor diagenetic alterations that are recognized in the Bandelier.

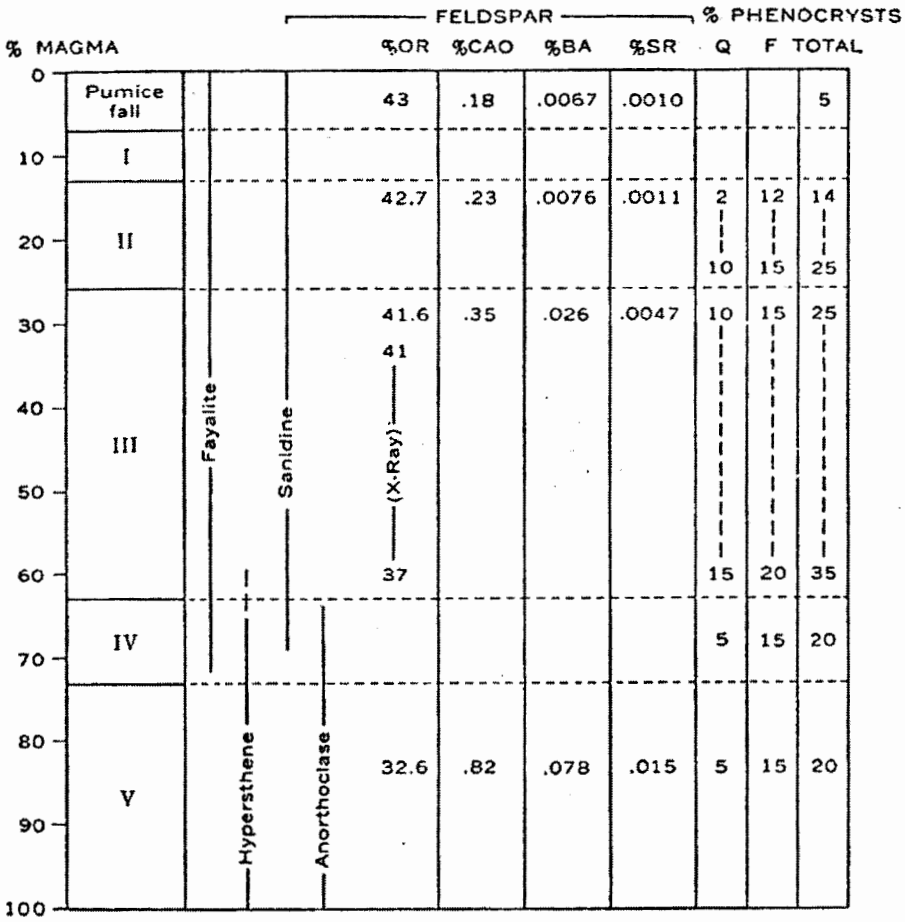

FIG. 14 - Summary of mineralogical data from subunits of the upper member of the Bandelier Tuff, showing the relative position of the subunits in the magma chamber and their relative magmatic volumes.

Although some scatter of values may be attributed to these processes, they seem not to significantly affect the major trends. The Bandelier, however, is very young, and older ash flows may show greater modification resulting from prolonged diagenetic alteration.

Data for Li_2O, Rb_2O, Pb, F, Cl, and TiO_2 shown in Figure 16 are

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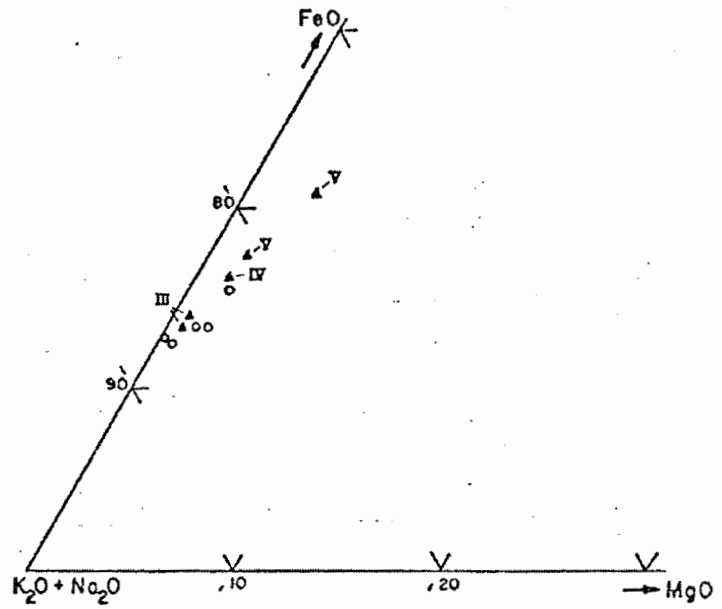

FIG. 15 - (K_2O + Na_2O) - FeO - MgO diagram for the Bandelier Tuff. Upper member, solid triangles; lower member, open circles. FeO = FeO + Fe_2O_3 recalculated as FeO.

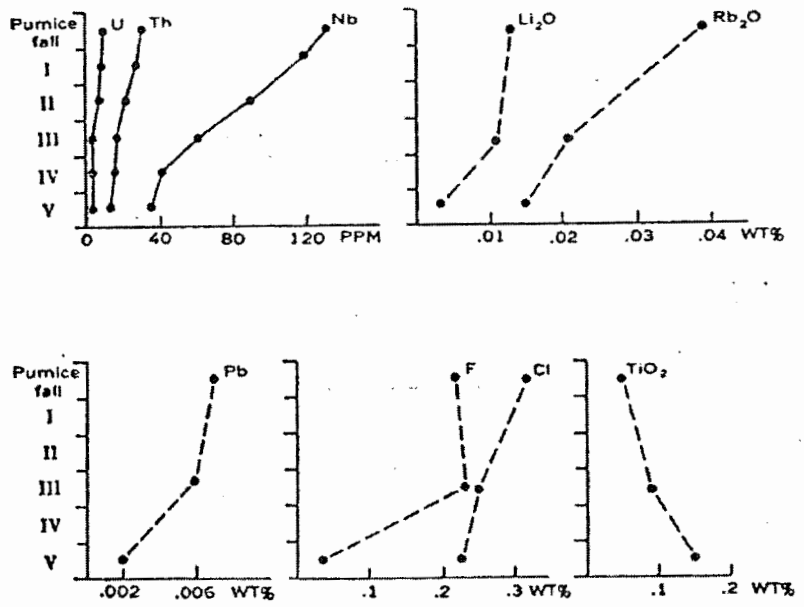

FIG. 16 - Distribution of minor elements in the upper member of the Bandelier Tuff, shown in sequence as in the magma chamber.

from 3 selected glass analyses. Although insufficient for detailed discussion, they show trends consistent with the U, Th, and Nb data.

Some Preliminary Conclusions

1) The upper Bandelier ash flows were erupted in a remarkably systematic way from a single magma chamber containing demonstrable physical and chemical gradients.

2) At least the first 30 cubic miles of ash flows record a systematic increase in emplacement temperature. The remaining 20 cubic miles probably continue the trend but documentation is more difficult.

3) The emplacement temperatures probably ranged from about 550°C to over 800°C. These approximate temperatures will be discussed more fully in a later paper but are based on welding and crystallization experiments (SMITH, FRIEDMAN, and LONG, 1958, and unpublished), phase relations, and other factors.

4) The emplacement temperature range seems best explained by the cooling effect of mixing with air in a vertical eruption column before the ash flows formed. The height of the column, and hence the amount of mixing may be related to a changing vapor pressure in the magma. The evidence implies that a falling vapor pressure is conducive to greater heat conservation, hence to successively higher emplacement temperatures during the course of the eruption. A higher vapor pressure at the top of the magma chamber is also implied, and whereas this condition is in agreement with some of our data, it is at variance with other data. More information is needed.

5) The bulk compositions of the upper member of the Bandelier show the first erupted material to be most salic and the last erupted most mafic. In a schematic way the evidence indicates a magma chamber (Fig. 17) with the most potassic feldspar crystallizing at the top, more sodic feldspar below; fayalite crystallizing at the top, hypersthene below; and U, Th, Nb, Pb, Li, Rb, F, and Cl concentrated upward in the liquid, Ba and Ti concentrated downward.

6) These gradients are perhaps to be expected in the magma chamber, but most significant is the fact that they can be reconstructed by means of detailed stratigraphic, mineralogical, and chemical studies of the ash-flow sheet.

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served, shows many physical and chemical parallels with the upper sheet. All evidence indicates that the two sheets, separated in time by about 400,000 years, had comparable histories and common origins; and that considered together they broaden our concepts of volcanic cycles.

The systematic eruptions of the Bandelier ash-flow sheets, and others like them, are remarkable, and careful studies should lead to more refined knowledge of the processes actually at work in magma chambers.

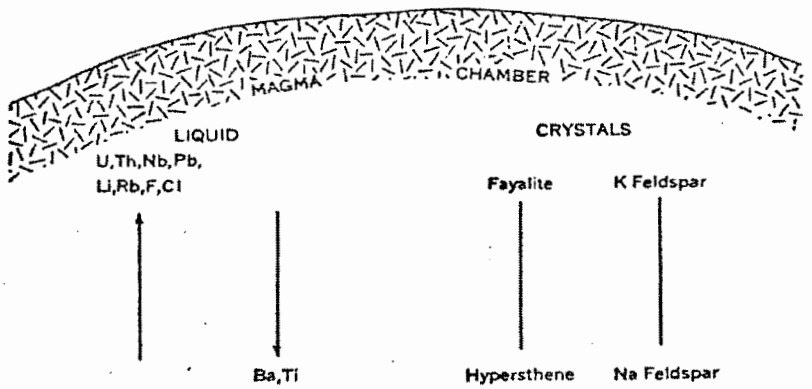

FIG. 17 - Schematic diagram showing gradations in composition of crystals and liquid in the magma chamber from which the upper member of the Bandelier Tuff was derived.

Recent work published or in progress by a number of workers indicates similarities among these silicic magmas that may permit us to limit the number of hypotheses for the origin and evolution of silicic volcanic rocks. Of the current work we should note that of RATTÉ and STEVEN (1964) in the San Juan Mountains of Colorado; LIPMAN, CHRISTIANSEN, and O'CONNOR (in press) in Nevada; ARAMAKI and UI (1965), ONO (1965, and personal communication), in Japan; and EWART (1965) in New Zealand.

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Discussion

A. EWART: We are particularly interested in the results of your study of the vertical variations within the Bandelier Tuff. Recently, similar variations were found and described from the Whakamaru Ignimbrite, Taupo Volcanic Zone. These included an upward enrichment in sodium, upward increase in total phenocryst content, quartz resorption, and upward decrease in modal plagioclase/quartz ratios. These were also interpreted as of primary (pre-eruption) origin.

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the basal portions of the various flow units, and if so, do these show different mineralogical and chemical characteristics from the enclosing rock?

R. L. SMITH: I think you are referring specifically to vitric lenticles that you found to be more potassic than their matrix. We have not found such lenticles in the Bandelier Tuff. However, speaking on the general problems of volcanic glasses, we do find in the United States, that the diagenetic hydration of glass may be accompanied or followed by chemical changes. The most obvious change is loss of sodium causing relative enrichment of potassium with respect to sodium. In many hydrated glasses, however, I have found also a real enrichment of potassium that I relate to low temperature reactions between the glass and ground or surface waters. I would suggest that this process might have altered the original chemistry of the Whakamaru lenticles, but for the fact that you have also found mineralogical differences.

K. YAGI: Is there any difference in the degree of welding within each subunit?

What minerals are formed as the products of devitrification in these deposits?

R. L. SMITH: Within each subunit differences in degree of welding are observed — that is, zones of greater welding alternate with zones of lesser welding; but the average porosity of the subunits decreases upward from one subunit to the next, suggesting a general upward increase in degree of welding and a progressive increase in emplacement temperature of the ash flows.

The products of devitrification in the Bandelier — specifically, the products of direct crystallization of the glass in shards and pumice — are invariably cristobalite and alkali feldspar. In the vapor phase zone these products of devitrification are accompanied also by tridymite, alkali feldspar, and iron oxides which have crystallized from vapors in vesicles and in interstices between shards.