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# ZONATION OF ALKALI FELDSPAR COMPOSITIONS IN THE TSHIREGE MEMBER OF THE BANDELIER TUFF IN PUEBLO CANYON, NEAR LOS ALAMOS, NEW MEXICO

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**Abstract**—In the Pajarito Plateau the Tshirege Member of the Bandelier Tuff is a compositionally zoned ignimbrite sheet, composed of, from base to top, cooling units I, II, III and IV, each formed of multiple pyroclastic flow and surge units. Flow units 1a and 2a are, respectively, the major components of cooling units I and II. This paper presents the results of electron microprobe analyses of 1200 alkali feldspar phenocrysts from the matrix (<2 mm grain size fraction) of the Tshirege Member in Pueblo Canyon and two additional sites. It documents the vertical compositional variation of alkali feldspars through the four cooling units in their proximal facies, and vertical and lateral compositional zonation within flow units 1a and 2a along flow direction. Cooling units I and II contain mostly grains of rim composition $Or_{36-44}$, whereas cooling units III and IV contain grains of rim compositions $Or_{25-44}$. The overall upward increase in proportion of alkali feldspar phenocrysts of progressively more sodic composition is interrupted by two trend reversals within cooling units III and IV. Flow units 1a and 2a show pronounced lateral (proximal to distal), and lesser vertical, compositional zonation. The first erupted material in an eruptive pulse traveled farthest, while the last erupted material was emplaced near the source. The observed trends are compatible with a model of laminar transport and en masse deposition. Caldera collapse early during eruption of Cooling Unit III is suggested by the presence of basal lithic breccias, high lithic content compared to the other cooling units, and the abrupt influx of feldspars from deep in the magma body. This altered the dynamics of magma withdrawal and eruption, causing eruption of many smaller pyroclastic flows and surges, and resulted in irregularities in the range of compositions tapped during subsequent eruption pulses.

## INTRODUCTION

The Valles caldera and associated Bandelier Tuff have been the sites of much of the pioneering work on resurgent calderas and compositionally zoned ignimbrites (Smith, 1960a, b; Ross and Smith, 1961; Smith et al., 1961; Smith and Bailey, 1966; Smith, 1979). Smith and Bailey (1966) first described vertical compositional zonation within the Tshirege Member of the Bandelier Tuff, documenting an upward change in modal phenocryst contents and average compositions of alkali feldspars and clinopyroxenes. In the present study 1200 alkali feldspar grains were analyzed by electron microprobe to determine in greater detail the lateral and vertical compositional zonation within the ignimbrite sheet. This paper documents the considerable complexity in compositional zonation within the Tshirege Member. The upward increase in range of feldspar rim compositions present is interrupted by reversals in individual pyroclastic flows and surges. Lateral zonation within two flow units is consistent with emplacement from a dense particulate flow which traveled in a laminar fashion.

## DEFINITIONS

The term ignimbrite is used to describe all deposits formed by the emplacement of pyroclastic flows. Surge beds refer to cross-bedded deposits emplaced by any type of pyroclastic surge. The matrix of an ignimbrite is the <2 mm size fraction, which consists of free crystal grains, ash, and small pumice lapilli and lithic clasts. A flow unit is material deposited from a single pyroclastic flow (Sparks et al., 1973). In places, it may resemble a composite of several flows because different lobes from the same flow may overlap, or undergo internal shearing (Fisher and Schmincke, 1984; Cole et al., 1993). Such multiple flow unit deposits become more prevalent in distal parts of a flow, and careful field examination is necessary to distinguish them from multiple pyroclastic flows (Fisher and Schmincke, 1984).

Sparks et al. (1973) described the typical products of a pyroclastic eruption as consisting of basal surge beds (layer 1), a pyroclastic flow unit (layer 2) and ash fall (layer 3). They further divided the flow unit into layer 2a, a basal fine-grained layer usually centimeters thick, and layer 2b, the overlying massive deposit. In this paper, layers 2a and 2b of Sparks et al. (1973) will be referred to as layers L2a and L2b, respectively.

A simple cooling unit is made from one or more pyroclastic flows which cooled as a unit without a break in time or cooling properties (Smith 1960a,b). A compound cooling unit is made of successive pyroclastic flows emplaced at radically different temperatures or emplaced over a time break which caused welding and crystallization patterns to deviate from those expected in a simple cooling unit (Smith, 1960a,b).

## THE BANDELIER TUFF

The Valles caldera and associated Bandelier Tuff are located in the Jemez Mountains volcanic field in northern New Mexico (Fig. 1), which became active before 13 Ma (Gardner et al., 1986; Self et al., 1986). The eruption of the Otowi Member of the Bandelier Tuff at 1.61 Ma (Izett and Obradovich, 1994) resulted in the formation of the Toledo caldera, which is coincident with, and possibly slightly larger than, the present Valles caldera (Goff et al., 1984; Self et al., 1986). Following eruption of the Otowi Member, the Cerro Toledo Rhyolite was erupted as tephra deposits and extrusive domes along ring fractures (Bailey et al., 1969; Heiken et al., 1986). The Tshirege Member of the Bandelier Tuff was erupted at 1.22 Ma, and resulted in the formation of the Valles caldera (Smith and Bailey, 1966; Izett and Obradovich, 1994).

The Otowi and Tshirege Members each consist of a basal pumice-fall bed overlain by a succession of pyroclastic flow and surge deposits. The thick intracaldera facies of the Otowi (up to 833 m) and Tshirege Members (approximately 1600 m) are much thicker than outflow deposits and are evidence that caldera collapse occurred during both eruptions (Nielson and Hulen, 1984). The Bandelier Tuff forms two extensive plateaus; the Pajarito Plateau to the south and east of the caldera, and the Jemez Plateau to the west (Fig. 1). Canyons have been cut into the plateaus in a radial pattern around the Valles caldera, providing excellent exposures of the Tshirege Member from proximal (near-source) to distal (far from source) areas.

## TSHIREGE MEMBER OF THE BANDELIER TUFF

The Tshirege Member consists of rhyolitic pumice (99%), dacite pumice (<1%), and rare syenitic crystal clots (<<1%). The crystal-rich (up to 35%) calc-alkaline rhyolite contains quartz and alkali feldspar, which together constitute 98% of the phenocrysts. Less than 2% of the rhyolite phenocrysts are mafic; they include olivine (fayalite), clinopyroxene (ferrohedenbergite to ferroaugite), orthopyroxene (ferrohypersthene), magnetite, and traces of apatite and chevkenite. The syenitic crystal clots contain anorthoclase grains intergrown with anorthoclase grains with plagioclase cores, orthopyroxene (ferrohypersthene to hypersthene) or clinopyroxenes (augite), Fe-Ti oxides, and apatite inclusions. These clots are found only in late erupted material and the intergrown intrusive texture, and evidence of interaction with the rhyolite magma, is consistent with an origin from magma body margins (Caress, 1995). The gray hornblende-bearing dacite pumice contains plagioclase, hornblende, biotite and two pyroxenes in a variably crystallized matrix, and is ubiquitous through the Tshirege Member (Balsley, 1988). Geochemical evidence shows the dacite and rhyolite magmas are unrelated, whereas chilled textures of the

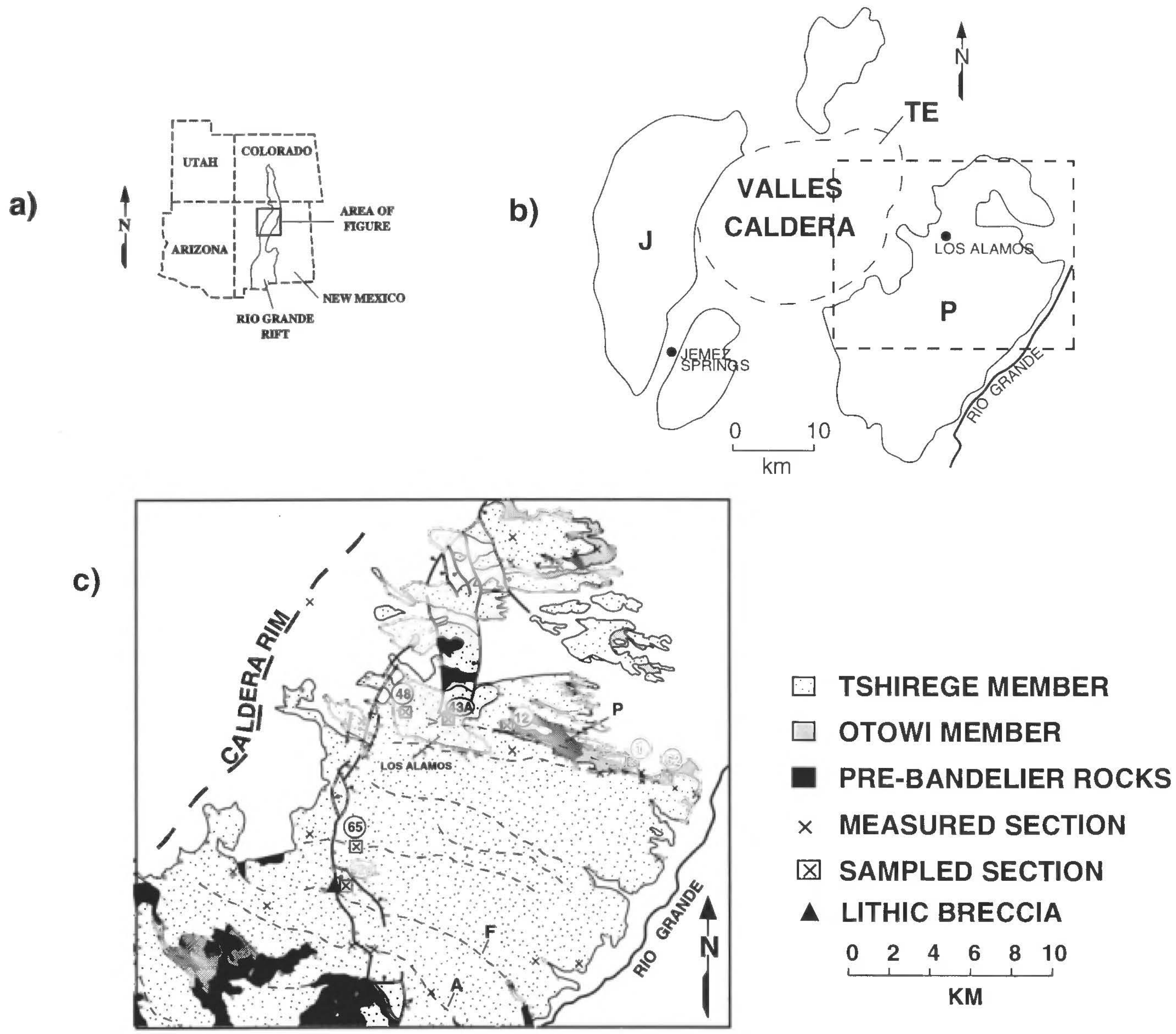


FIGURE 1. a) Location of Jemez Mountains volcanic field in northern New Mexico shown in box. b) Distribution of the Bandelier Tuff. Dashed subcircular line is present topographic rim of the Valles caldera and Toledo embayment, a feature which predates eruption of the Otowi Member. P = Pajarito plateau; J = Jemez plateau; TE = Toledo embayment. Modified from Smith et al., 1970. The dashed rectangle shows area enlarged in figure 1c. c) Locations of measured stratigraphic sections of the Tshirege Member. Those measured sections used for sampling are numbered. Dashed lines are canyons. P = Pueblo Canyon; F = Frijoles Canyon; A = Alamo Canyon. After Smith et al. (1970).

dacite pumice indicate it was injected into the rhyolitic magma body shortly before eruption (Balsley, 1988; Wolff, personal commun., 1993).

Upward through the Tshirege Member, quartz sharply decreases, sanidine gives way to anorthoclase, olivine disappears, and orthopyroxene appears (Smith and Bailey, 1966). The average potassium content of the feldspars decreases upward, with sodic sanidine ($Or_{43}$) at the base trending to anorthoclase ($Or_{33}$) at the top (Smith and Bailey, 1966). Warshaw and Smith (1988) used several geothermometry methods to determine that magma temperature increased from 700°C in the Tsankawi pumice bed to 850°C in the uppermost subunit. Smith and Bailey (1966) and Smith (1979) interpreted the compositional zonation of the Tshirege Member to represent systematic withdrawal from a vertically compositionally and thermally zoned magma chamber from which material at the top erupted first. Higher concentrations of U, Th, Nb, Pb, Li, Rb, F and Cl, as well as K-rich sanidine and Fe-rich pyroxene, were found near the top of the chamber, with downward transitions to more Na-rich feldspars and less Fe-rich pyroxene, and greater Ba and Ti concentrations (Smith & Bailey, 1966; Smith, 1979; Warshaw and Smith, 1988).

## STRATIGRAPHY OF THE TSHIREGE MEMBER IN THE PAJARITO PLATEAU

Thirty-five stratigraphic sections were measured in the Pajarito Plateau (Fig. 1). The Tshirege Member in the Pajarito Plateau is a compound cooling unit, consisting of four cooling units, each containing one or more pyroclastic flow and surge units emplaced at a similar temperature (Table 1; Fig. 2). Cooling units I, II and III are simple cooling units, while cooling unit IV is itself a compound cooling unit. In proximal sites, the entire section is densely welded, but in medial to distal areas the breaks between the four cooling units are pronounced. The cooling units can be distinguished in the field by relative degrees of welding, lithic content, and marker beds, mostly surge deposits. Small flow units are local, but larger ones in cooling units I and II can be traced over the entire plateau. Flow unit boundaries were identified by an abrupt, laterally continuous change in size or concentration of lithic or pumice clasts. The presence of layer L2a is the most reliable indicator of a flow unit boundary, but was not always present.

Smith and Bailey (1966) divided the Tshirege Member into 5 subunits

TABLE 1. Description of cooling units of the Tshirege Member of the Bandelier Tuff in the Pajarito Plateau. Proximal refers to locations 6-10 km from topographic caldera rim; medial to locations 10-15 km from the rim, and distal to locations 15-20 km from the rim. In the relative welding column, 1 is least welded, 4 is most welded.

| Cooling Unit | Description | Thickness | Lithic Content | Relative Welding | Present |
|---|---|---|---|---|---|
| IV | Complex package of pyroclastic flows and surges. Can be divided into 3 subunits. IVc. Densely welded, purple, multiple pyroclastic flows and surges. It is the anorthoclase subunit of Smith & Bailey (1966). IVb. Pink, less densely welded than a or c. Interbedded flows and crystal-rich surge beds. IVa. Gray, densely welded, base and top marked by crystal-rich surges. Basal vitrophyre 10 cm thick, with local lithophysae. | 30 m proximal | Very low | 4 | Proximal, and SW plateau |
| III | Unit 3 consists of multiple flow units, minimum of three. Lithic rich, with proximal basal lithic breccia zones. Variety of pumice types and lithic compositions, including pink welded ignimbrite clasts. | 40 m proximal, 10 medial (eroded) | High | 2 | Proximal to medial |
| II | Base marked by crystal-rich surge unit, up to 0.5 m thick. Overlying is single flow unit (Flow Unit 2a) with local basal pumice concentration. Forms prominent pink cliffs in Pajarito plateau. | ~50 m proximal, 5 m distal | Low | 3 | Entire plateau |
| I | Tsankawi pumice fall bed forms base, overlain by ash-rich surges (0.5-1m thick). Above surges is the major Flow Unit 1a (FU1a); in some proximal sites local flow unit underlies FU1a. FU1a comprises ~2/3 of Unit 1, and is overlain by multiple (up to 15) small flows and surges. Prominent pumice concentration zones from these flow units provide a marker for the approximate top of Fu1a. In medial to distal areas, a distinct erosional horizen from interaction of welding and vapor phase processes is present (vapor phase notch). | 15-60 m Variable, fills in topographic depressions | Low | 1 | Entire plateau |

based on mineral content and relative emplacement temperature as determined by degrees of welding or devitrification, but noted that such a division might not correspond to depositional divisions. The present study follows the practice of Crowe et al. (1978) in mapping according to depositional boundaries, in which boundaries between cooling units represent interruptions in the eruption (Fig. 3). Crowe et al. (1978) described three cooling units in the eastem part of the Pajarito Plateau; this study adds unit IV, present mainly in the western part. Cooling units are designated by Roman numerals (I-IV). Flow units are designated by Arabic numerals to indicate cooling unit, and letters are used to describe stratigraphic position within the unit, with **a** as the lowermost flow in a cooling unit. Only flow units that can be correlated over the plateau are numbered (Fig. 2).

Cooling units I and II consist of large-volume pyroclastic flow units and subordinate pyroclastic flow and/or surge beds. Cooling units III and IV contain pyroclastic flow units which are thinner than in earlier cooling units. There is evidence of time breaks between cooling units II and III (zone of decreased welding) and between cooling units III and IV (basal vitrophyre in cooling unit IV). The basic depositional stratigraphy of the Tshirege Member is overprinted by welding, devitrification, and vapor phase crystallization zonation (Smith, 1960a; Smith and Bailey, 1966).

### Unit I

Cooling units I and II are present throughout the Pajarito Plateau. The base of cooling unit I is composed of the Tsankawi pumice beds, and overlying ash-rich surge beds (Fig. 2, Table 1). Locally a small (meter-thick) flow occurs between the surges and flow unit 1a. Flow unit 1a (FU1a), the most voluminous flow unit within the Tshirege Member, consists of a layer L2a (6 cm thick) overlain by a massive layer L2b up to 30 m thick. Within FU1a is a minor normal grading of lithics, and reverse grading of pumice. The lithic content is 1–2%, and ground layers or segregation pods are absent. Approximately 1 km downstream of locality 1, two pumice concentration zones, 50 and 80 cm thick, midway through FUIa suggest that the flow had divided into two lobes (Fig. 4).

Up to a dozen thin pyroclastic flow units and crystal-rich surge beds overlie FU1a. The pyroclastic flow deposits are up to 1 m thick, and pumice is concentrated near the tops of several of them. Where contacts between these thin flow units cannot be distinguished because of vapor phase alteration and weathering, three or four pumice concentration zones mark their location. These small flows are overlain by a crystal-rich surge layer described by Fisher (1979), which marks the base of unit II.

A distinctive "vapor phase notch" little more than halfway up through FU1a commonly coincides with a weathered gray to pale pink band approximately 0.5 m thick (Fig. 2). Crowe et al. (1978) suggested that this zone resulted from the interaction of vapor phase alteration and welding. The continuity in maximum lithic and maximum pumice clast size measurements and feldspar chemistry across the notch, as well as the absence of other indicators of a flow unit boundary, confirms that this feature is not a primary depositional feature.

### Unit II

Unit II is welded throughout its thickness, forms the distinctive orange-tan cliffs that cap much of the plateau, and in Pueblo Canyon consists of a single flow unit, flow unit 2a (FU2a), above a crystal-rich surge bed. In the more distal areas (localities 1 and 62) a basal pumice concentration zone is present. No systematic vertical trends were noted in lithic size or concentration, and lithic content is 1–2 %. Two apparent flow units are present in FU2a from about 1 km downstream of locality 1 to the most distal exposure. Both have upper pumice concentration zones, and the upper apparent flow unit has a thin basal layer L2a. The change from one to two flow unit deposits in the same area in both FU1a and FU2a suggests that two lobes from each flow overlapped as a result of diversion around a local obstacle.

### Unit III

Cooling unit III is present in proximal (6–10 km) to medial (10–15 km) areas, and is rich in lithic clasts compared to the other units. A matrix-supported basal lithic breccia in Frijoles Canyon (9 km from the caldera rim) is 3 m thick, and contains lithic clasts $\leq$25 cm in size, of variable composition (Fig. 1). Above the breccia zone, lithic concentration varies between 5–15%. Cooling unit III contains multiple flow units (at least three, probably more) which cannot be traced laterally due to vapor phase and secondary alteration.

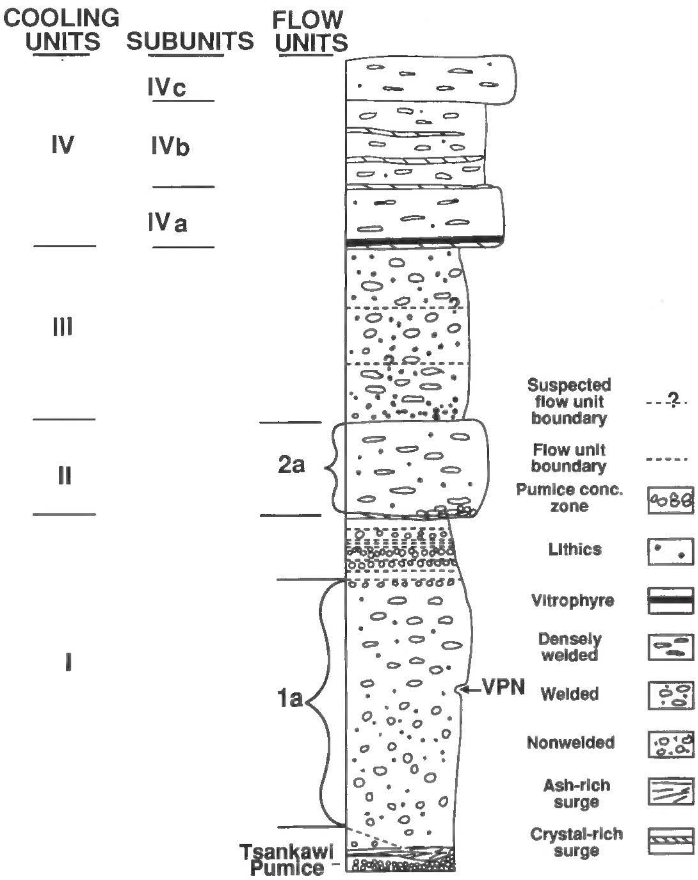


FIGURE 2. Composite stratigraphic section of the Tshirege Member of the Bandelier Tuff in the Pajarito Plateau. Thickness of various units differs with location. Cooling unit III consists of multiple flow units (minimum of 3) that cannot be correlated laterally. Subunits divide layers of significantly different welding character in the complex cooling unit IV; all of cooling unit IV is more densely welded than the other cooling units. VPN = vapor phase notch, a prominent horizon of preferential weathering formed due to a combination of vapor phase and welding processes.

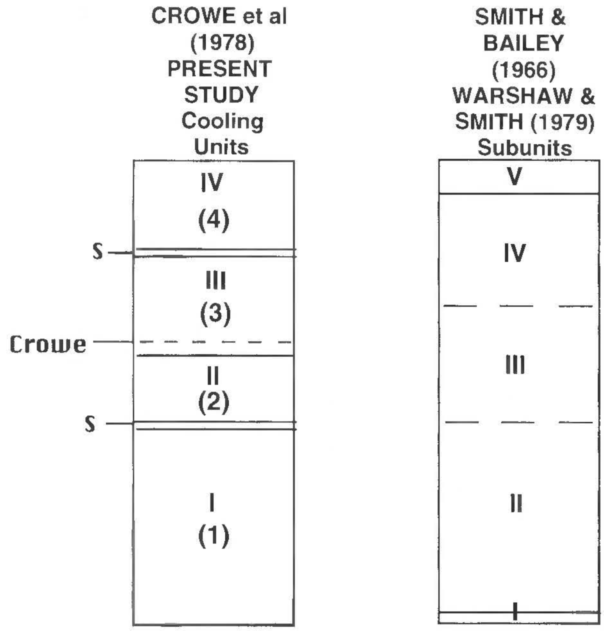


FIGURE 3. Correlation between the stratigraphy in the Pajarito Plateau used in this study, and by Crowe et al. (1978), and the subunits defined by Smith and Bailey (1966). Cooling units in the present study are designated by Roman numerals; numbers in parentheses are cooling units of Crowe et al. (1978); dashed line labeled "Crowe" is the boundary between units 2 and 3. In the present study, a strong increase in lithic content is found at the base of cooling unit III, but Crowe et al. (1978) included the base of this lithic-rich zone in the top of his cooling unit 2. The location of the dashed boundaries between Smith and Bailey's (1966) subunits are placed approximately. S = crystal-rich surge bed.

### Unit IV

Cooling unit IV is restricted to proximal localities, except at the southernmost part of the plateau, where R. L. Smith (personal commun., 1991) identified a fine-grained equivalent. Cooling unit IV is a compound cooling unit, and is divided into three subunits, which may be identified on the basis of color and relative degree of welding (Fig. 2; Table 1). Unit IV has a generally low (<2% volume) lithic content.

## METHODS

### Sampling

Alkali feldspars from the Tshirege Member were selected as the target of this study because of their abundance and lack of alteration, and because variation in feldspar compositions had been previously documented (Smith and Bailey, 1966). The alkali feldspars were derived from the zoned rhyolite magma, or rarely from crystal clots thought to be derived from the chamber margin. Pueblo Canyon was selected for sampling because it is accessible, and oriented parallel to flow lineations determined optically by Elston and Smith (1970) and by anisotropy of magnetic susceptibility by MacDonald and Palmer (1990).

Four stratigraphic sections in Pueblo Canyon provided data on lateral and vertical zonation within FU1a and FU2a (Figs. 1, 4). A fifth site (locality 48) provided samples from cooling unit III. Two additional sites (localities 65 and 52a) south of Pueblo Canyon, provided data from unit IV. Most samples from cooling units III and IV came from pyroclastic flow units, but sample 367 (locality 52a) was from the crystal-rich surge bed between subunits IVa and IVb (Fig. 4).

In medial to distal areas, cooling and flow unit boundaries within Pueblo Canyon are clearly discernible in the nonwelded to welded deposits (Fig. 4). Closer to the caldera, however, all cooling units become more welded, densely so at the most proximal localities. As the units become more welded, flow unit boundaries become indistinct and the vapor-phase notch in unit I disappears, as does the crystal-rich surge layer between units I and II. The multiple pumice concentration zones that mark the approximate upper limit of FU1a are absent or indistinguishable. At locality 43a the boundary between units I and II is marked by an upward transition from a zone containing pumice with a "sugary" texture, caused by replacement of glass by cristobalite, alkali feldspar, and tridymite (Smith, 1960a), into a zone in which the flattened, devitrified pumice lack this sugary texture (Fig. 4).

Samples from FU1a and FU2a were analyzed from the massive bodies of each flow (layer L2b) . The bottom samples at each site were collected 2–6 cm above the base of layer L2b and the upper samples were taken as close to the top of each flow unit as possible. The sample for upper FU1a (sample 432) at locality 43A was collected at a level several meters below the transition between cooling units I and II, to avoid thin flow units overlying FU1a.

### Electron microprobe analyses

In every thin section 40 alkali feldspar grains from the matrix were selected for analyses during a point-count. Selected grains were euhedral or broken such that rim and center were still distinguishable. Grains of the entire size spectrum were analyzed in each sample. The alkali feldspars from the rhyolite magma consists of grains of sanidine to anorthoclase composition up to 3 mm long, and rare large and fractured anorthoclase grains up to 5 mm long found only in unit IV (Caress, 1995). Grains from syenitic clots are up to 2 mm long. Analyses with a 5 micron diameter beam from a Cameca MBX electron microprobe at Los Alamos National Laboratory were performed at the rim (10 microns from grain edge) at the core and at 1-12 intermediate sites. Grains in vapor phase zones commonly have a thin (10-50 micron) alkali feldspar jacket. Rim analyses for these grains are of the original, pre-vapor phase grain mar-

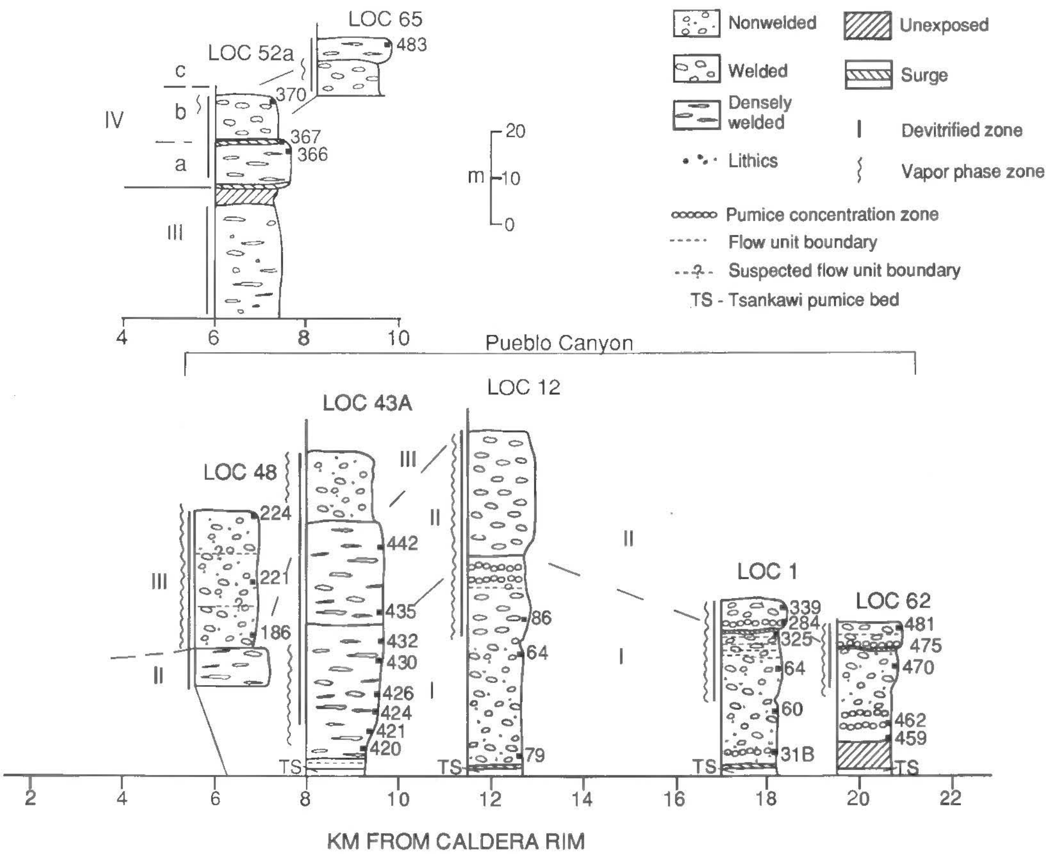


FIGURE 4. Sampling sites in stratigraphic sections used in study, plotted against distance from caldera rim. LOC = locality. Filled squares show level from which samples were collected; numbers next to squares are sample numbers. Cooling units shown in Roman numerals. The vapor phase zone marked next to the sections indicates the presence of pumice in which glass has been replaced by cristobalite, alkali feldspar, and tridymite, imparting a "sugary" texture in the field. FU1a = Flow unit 1a, FU2a = Flow unit 2a.

gin. Only rim composition data will be considered in this paper, because it is the data most likely to reflect pre-eruption depth in the magma body. For more detailed information on sample preparation and microprobe analyses parameters, see Caress (1995).

Alkali feldspar grains from the matrix rather than from pumice were used to document compositional variation within the Tshirege Member, because the matrix is presumed to provide a better measure of average composition at a site than do individual pumice clasts. Pumice from various levels within the magma chamber commonly coexist next to each other in a deposit, and this tendency increases in the upper part of the Topopah Spring Member of the Paintbrush Tuff (Schuraytz et al., 1989). Large numbers of pumice clasts would be required to establish the presence or absence of subtle compositional zonation from one site to another.

### Contamination

Samples from 10 rhyolite pumice clasts were analyzed to determine the compositional range of the Tshirege rhyolite, and test for the presence of matrix grains from pre-Bandelier rocks. Alkali feldspar from pre-Bandelier rocks have a more potassic composition than the most potassic Tshirege grains (Gardner, 1985), and only three grains of these compositions were among the 1200 matrix grains analyzed. Alkali feldspars from the Cerro Toledo Rhyolite and from the Otowi Member are indistinguishable from Tshirege Member grains by microprobe analyses. However, there is no field evidence to suggest the Tshirege flows had scoured into pre-Tshirege deposits in Pueblo Canyon.

## RESULTS

### Vertical zonation through the Tshirege Member

Alkali feldspars from the matrix range in rim composition from anorthoclase ($Or_{25}Ab_{70}An_5$) to sodic sanidine ($Or_{44}Ab_{55}An_{01}$). This is consistent with the compositional range found within the pumice clasts (Caress, 1995), and in rims of grains in syenitic clots. Because the compositions for alkali feldspars lie close to the Ab-Or join on a ternary plot, the compositions will be designated by Or endmember content. The lack of correlation between rim compositions and degree of vapor phase crystallization or devitrification in FU1a at localities 12, 1 and 62 (12, 16.5, and 20.5 km from rim) suggests that compositional variations reflect pre-eruption differences in the feldspar compositions (Figs. 4, 5). The rims are presumed to have been in equilibrium with pre-eruption magma.

The overwhelming majority of grains from cooling units I and II have rim compositions of $Or_{36-44}$. Grains of composition $Or_{<36}$ are present from the base of unit III upward. All vertical sections show a general upward trend for increasingly greater feldspar diversity, including greater proportions of more sodic feldspars (Fig. 5). However, there are local reversals to this trend, particularly in units III and IV. Sample 224 in cooling unit III has a larger proportion of more potassic grains ($Or_{>36}$) than lower sample 221, and sample 367 (from a crystal-rich surge unit) has a significantly greater proportion of the most potassic grains ($Or_{40-44}$) than samples from pyroclastic flows above and below (Fig. 5). In subunit IVc (sample 483), the alkali feldspar population consists almost entirely of anorthoclase ($Or_{<37}$). This is the only sample in which grains of $Or_{>40}$ were absent, and it contains the greatest percentage (20%) of syenitic crystal clot grains of any of the samples.

### Patterns of zonation within flow units

Flow units 1a and 2a are zoned both vertically and horizontally with respect to alkali feldspar compositions. The most distal deposits of FU1a (locality 65) contain feldspar with the highest potassium content ($Or_{36-44}$), and the smallest compositional range. This pattern is maintained through the medial sites. In the most proximal site, only the two basal samples have the same narrow range of high potassium feldspar as the more distal samples. Above them is an upward trend toward a progressively larger proportion of grains of lower Or content.

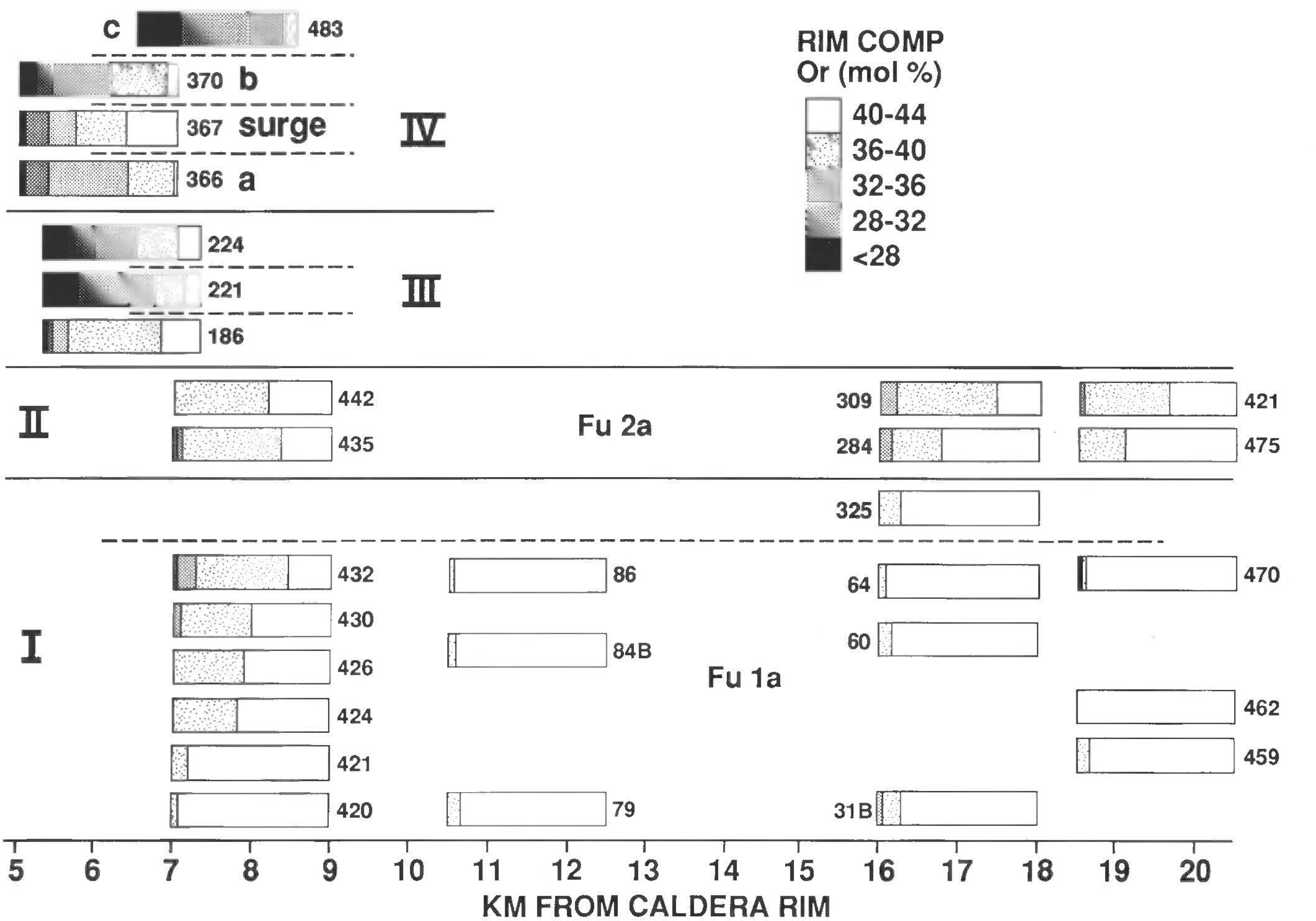


FIGURE 5. Distribution of alkali feldspar rim compositions from samples shown in Figure 4. Numbers are sample numbers. Bars show percentage of grains from each sample (n=40) that are in different rim composition categories as determined by Or endmember content. FU1a = flow unit 1a, FU2a = flow unit 2a.

Flow unit 2a also shows predominantly lateral zonation, with secondary vertical zonation at the distal, rather than the proximal site (Fig. 5). The most distal samples have the smallest compositional range, the greatest proportion of potassic grains and an upward trend toward less potassic feldspars. In general, compositional variation increases toward the vent, but at locality 1 (16 km from the caldera rim), the proportion of composition $Or_{32-36}$ reaches a peak.

Figure 6 shows the percentage of grains with rim composition $Or_{>40}$ for proximal (locality 43a) versus distal (locality 62) sites in Pueblo Canyon. Spread between proximal and distal values is greatest for most of FU1a, and is measurably smaller for basal cooling unit I and upper cooling unit II. Upward in cooling units III and IV, the percentage of grains with $Or_{>40}$ decreases, with the exception of sample 367, the crystal-rich surge between subunits IVa and IVb.

## DISCUSSION

The following discussion assumes that the composition of an alkali feldspar grain is a measure of pre-eruption depth in the vertically zoned magma body proposed by Smith (1979). The more sodic its rim, the deeper a grain's position was in the magma body before eruption.

### Dynamics of magma withdrawal

The general upward trend toward material of increasingly larger compositional range, and larger proportion of more Na-rich feldspars, is consistent with models that predict simultaneous tapping of different levels within a density-stratified magma body as eruption proceeds (Blake, 1981; Spera 1984; Spera et al., 1986; Blake and Ivey, 1986; Trial et al., 1992). According to these models (Fig. 7), magma can be erupted simultaneously from widely separated horizontal and vertical locations in the pre-eruption magma chamber (Blake, 1981). As eruption proceeds, the extent of potential vertical mixing increases (Spera, 1984). The perturbations from the upward compositional trends in samples 224 and 367 indicates variability in depth and degree of sampling between different eruption pulses.

Figure 7 shows eruption from a vertically zoned magma body, which is tapped at progressively deeper levels as eruption proceeds. Dashed lines connect magma parcels that will arrive at the conduit at the same time. In this case, the most potassic feldspar compositions (**a**) are found at the roof, and the compositions change downward to less potassic compositions (**b**, **c**). If a relatively constant discharge rate is assumed, the maximum withdrawal depth and the proportion of grains from lower levels will increase with time. Combined data from the two flow units indicate a general trend for the earliest erupted material (with highest average Or content, and most limited compositional range) to travel the farthest. The last erupted material remained near the source (Fig. 7). In the distal and medial zones of FU1a, most of the flow is potassic ($Or_{40-44}$) with a narrow compositional range. Only a thin band of this material is preserved at the base of the proximal locality (locality 43a).

FU2a also shows lateral zonation but samples from the medial locality 1 (17 km from the caldera rim) have a slightly greater proportion of more sodic grains than those samples from more proximal or distal sites. They could be labeled as late erupted material on the basis of composition, but there is no evidence for the complicated field relationships required for such an interpretation. Instead, distal and medial FU2a are interpreted to record progressive deeper withdrawal from the chamber during the waxing stage of eruption, while the proximal material represents reversion back to a lesser maximum depth of withdrawal with a waning discharge rate (Spera et al., 1986).

Following eruption of FU1a, there was a reversal to higher potassium content and lower diversity in small overlying flows (sample 325) and in early material from FU2a. This may demonstrate partial recovery of

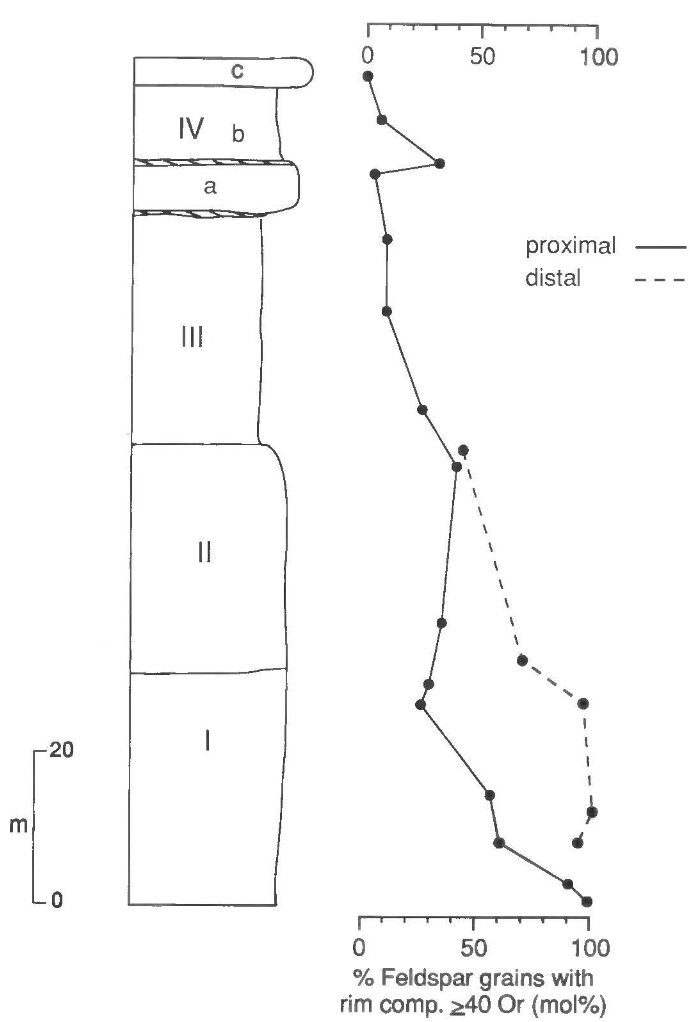


FIGURE 6. Plot showing lateral change in feldspar composition distribution. Filled dots are percentage of grains with rim composition $Or_{>40}$. Proximal samples are plotted to vertical scale. Sample sites in distal (Loc. 62) sites are plotted at levels proportional to their levels within the flow unit, to compensate for difference in thickness of these units from proximal to distal localities.

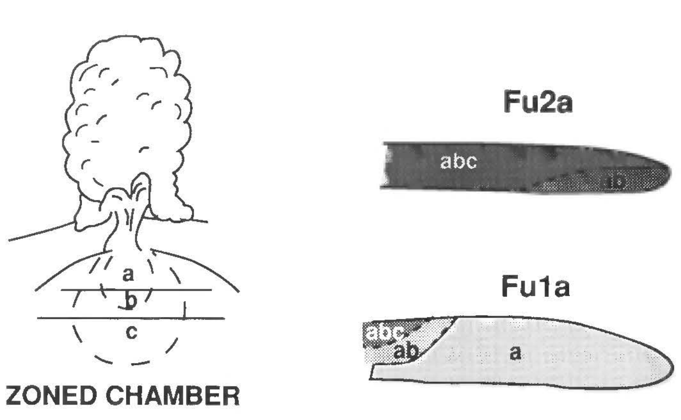


FIGURE 7. Left diagram shows eruption from a vertically zoned magma body, with the most evolved magma (with feldspar composition **a**) at the top. Magma parcels along the dashed subcircular lines arrive at the conduit concurrently. As eruption proceeds, successively deeper levels are tapped, and the compositional range of erupted material increases (Blake, 1981; Spera, 1984). Right diagram shows observed and extrapolated compositional zonation of flow units 1a and 2a. The earliest erupted material contains mostly feldspar of the most potassic composition (**a**). As eruption proceeds, progressively deeper layers within the chamber are tapped, and the composition of erupted feldspars changes to **ab** (compositions **a** + **b**) and then **abc**.

magma body zonation between eruptive pulses, as suggested by Spera et al. (1986). During eruption, compositional layers in a magma chamber were drawn up toward the conduit, but between the FU1a and FU2a eruptive pulses the magma redistributed itself in a gravitationally more stable manner. However, the composition in early erupted material of FU2a did not revert completely to the restricted compositional range found in the earliest FU1a, but to a mixture with smaller proportions of less potassic feldspar ($Or_{36-40}$) (Fig. 5). This indicates that recovery was not complete, and that each new eruptive pulse inherited some degree of mixing from previous pulses. An alternative explanation is that the separate flows or surges tapped different cupolas on top of the magma chamber. However, if eruptions occurred from a previously untapped cupola, presumably the first erupted material would consist only of the most evolved magma and would contain only the most potassic feldspars.

### Pyroclastic flow modeling

Researchers have debated whether the material in massive pyroclastic flows such as FU1a and FU2a was transported primarily as plug or laminar flow (Sparks, 1976; Wright and Walker, 1981; Freundt and Schmincke, 1985, 1986) or as part of a turbulent, stratified flow (Fisher, 1966, 1993; Valentine, 1987; Branney and Kokelaar, 1993). Plug and laminar flow are high-concentration, poorly expanded, non-turbulent particulate flows, whereas turbulent flows are expanded, low density flows, in which individual particles move in random directions and velocities. Plug and laminar flows move as a body, and presumably stop en masse, forming a deposit that is essentially a frozen flow (Sparks, 1976; Freundt and Schmincke, 1985; Battaglia, 1993). A basal zone of high velocity gradient and shearing produces layer L2a by dispersive forces (Sparks, 1976). In laminar flow, flow paths of particles are parallel, and there may be a vertical velocity gradient in the material above layer L2a. In plug flow the material above the basal 2a layer moves as a single mass (Sparks, 1976; Valentine and Fisher, 1986). In turbulent flows, material is transported in an expanded, turbulent system, and deposition occurs by successive aggradation from a basal high-concentration zone (Fisher, 1966; Branney and Kokelaar, 1993; Fisher et al., 1993).

Documentation of compositional zonation within individual flow units provides an opportunity to test these hypotheses. In pure plug flow, compositional zonation should be preserved laterally, as the earliest material erupted would travel the farthest, and the latest would be deposited near the vent. A flow unit deposited from progressive basal aggradation (turbulent model) would show vertical stratification, as earliest erupted material would be deposited at the base, and last erupted material would be deposited on top (Fisher, 1966; Branney and Kokelaar, 1993). Laminar flow could produce a range of zonation patterns, from dominantly lateral as the velocity gradient approaches zero above the basal zone (plug flow), to dominantly stratified as the velocity gradient within the flow body becomes more extreme, and upper layers travel substantially farther than lower layers. Within both FU1a and FU2a is evidence that proximal parts of the pyroclastic flows have overridden slightly earlier erupted material (Fig. 7). This suggests the flows were transported primarily by laminar flow, in which the upper material moved slightly faster and farther than lower material. This vertical zonation, however, is minor compared to the lateral compositional zonation.

The apparent flow unit boundary within distal FU2a was interpreted as separating flow lobes of the same pyroclastic flow. It is also possible that this boundary resulted from shearing as the flows became less fluidized with distance from the vent (Cole et al., 1993). The two samples analyzed are from the base of the lower lobe and top of the upper lobe, and are insufficient to show detailed compositional variation which could shed light on this problem.

### Caldera collapse

The great (1600 m) thickness of intracaldera facies of the Tshirege Member (Nielson and Hulen, 1984) indicates that caldera collapse occurred during eruption. A sudden increase in compositional range of feldspars, proximal lithic zones, and abundant lithics are consistent with caldera collapse, which began early during eruption of unit III. The abrupt influx of material from deep in the chamber could be the result of a sudden change in discharge rate (Spera et al., 1986) or collapse of caldera floor blocks into the chamber (Blake and Ivey, 1986). The systematic and regular monotonic change in composition through eruption of units I and II indicate an overall steady discharge rate during successive eruptive pulses (Spera et al., 1986) without major fluctuations. However, units III and especially IV are characterized by eruption of multiple small flows and surges, with significant time breaks between some of them. The variable sampling depth in successive flows and surges in units III and IV indicate variability in magma withdrawal dynamics, which could be the result of changes in discharge rate or vent geometry (Spera et al., 1986). Collapse of the caldera floor blocks into the magma chamber would entail changes in vent locations, size and shape, and probable disruption of density stratification. These changes could account for the change in eruption behavior between cooling units II and III.

## CONCLUSIONS

Complex vertical and lateral zonation of alkali feldspar compositions are interpreted as results of interactions of magma chamber zonation, magma withdrawal, and eruption and pyroclastic flow dynamics. Fluctuations in discharge rate, particularly during the eruption of cooling units III and IV, led to considerable variation within the overall compositional trend. Zoning that is primarily lateral, and secondarily vertical in flow units 1a and 2a of the Tshirege Member, is strong evidence that these deposits were emplaced by a laminar high-density particulate flow. Vertical zonation at a site, including total compositional range present, is dependent upon distance from the caldera rim (Fig. 5). Samples taken from the most distal site from units I and II represent only material from the upper levels of the magma chamber, whereas a section in these same units taken at the most proximal site also contains material from deeper in the chamber.

A zone near the base of unit III enriched in accidental lithic clasts is correlated with the main stage of collapse of the Valles caldera. Subsequent disturbances in the magma chamber due to collapse dynamics can account for the variability in erupted compositions, influx of material from deeper in the magma body, and change to eruption of multiple small flows and surges.

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