Origin of broken phenocrysts in ash-flow tuffs

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ABSTRACT

Surprisingly little attention has been devoted to the textural nature of phenocrysts of feldspar and quartz in tuff. Although many geologists have briefly alluded to “broken” phenocrysts, none have addressed their origin in any detail. Petrographic study of 117 cooling units in the middle Tertiary ash-flow province of the Great Basin, United States, provides a basis for characterization of the shapes and for interpretation of the origin of felsic phenocrysts in ash-flow tuffs. Although not proven to be wholly ineffective, breakage of phenocrysts by mutual impact in the erupting magma and pyroclastic flow is doubtful for at least four reasons. First, the statistical probability of mutual collision between phenocrysts diminishes exponentially as their proportion to vitroclasts diminishes (e.g., only 1% probability for 10% phenocrysts); collision is less likely if pyroclasts move by laminar rather than turbulent flow. Second, the coating of glass and/or melt on the phenocrysts provides a cushion that absorbs the impact force. Third, plagioclases broken by impact in the laboratory have unusual shapes unlike those seen in Great Basin tuffs. Fourth, euhedral phenocrysts of feldspar are commonplace in many Great Basin tuffs, and in some they constitute a significant proportion of the phenocrysts, indicating that mutual impact does not modify all intratelluric crystals during explosive eruption.

The two most populated categories of phenocryst shape in Great Basin tuffs probably correspond to what has been previously called “broken” phenocrysts. Somewhat less than half of the plagioclase and many sanidine phenocrysts are subhedral to anhedral. These are similar in shape, size, and composition to grains in polycrystalline aggregates within the same thin section. Kindred aggregates and discrete phenocrysts could have been derived from holocrystalline to partly crystalline material in the magma chamber that was disaggregated to varying extents during explosive eruption. More than half of the plagioclase and all of the quartz phenocrysts in Great Basin tuffs consist of irregularly shaped fragments with cuspsate, embayed outlines, resembling pieces of a jigsaw puzzle, which we call phenoclasts. Inclusions of glass are broken and are especially evident in larger, more or less whole crystals. Textural features of some phenocrysts in cognate pumice clasts in the tuffs reveal that they broke apart while still in the vesiculating but unfragmented magma. As the erupting magma decompressed, vesication of the melt that was entrapped at higher pressures as inclusions within the phenocrysts blew them apart, forming the phenoclasts.

Shapes of felsic phenocrysts in volcanic rocks provide insight into their mode of emplacement. Euhedral phenocrysts are common in ash-flow tuffs as well as lava flows. Phenoclasts, however, are diagnostic of ash-flow tuffs, because they do not occur in Plinian ash-fall deposits and are rare in lava flows. These textural contrasts are useful for interpretation of generally older, but in any case altered and recrystallized, volcanic rocks. In such rocks, critical groundmass features and field relations that could provide clues to their origin have been obscured, but the shapes of relict phenocrysts are commonly well preserved.

INTRODUCTION

Although ash-flow deposits have been the subject of numerous investigations over the past three decades, especially since the classic work of Ross and Smith (1961), no study has directly addressed in any detail the textural character and origin of their included “broken” phenocrysts. Virtually all of the textural descriptions of pyroclasts deal only with the vitroclasts (pumice fragments and glass shards). However, broken phenocrysts, together with the associated vitroclasts, have been considered for 200 yr to be the hallmark of deposits derived from explosive volcanic eruption (e.g., Cas and Wright, 1987; see Williams, 1926, for early references). Fisher and Schmincke (1984, p. 105) noted “The rapid decline of pressure during explosive eruption commonly causes breakage upon ejection or impact . . . Broken crystals are especially characteristic of ash-flow tuffs.” Henry and Wolff (1992) concluded that broken phenocrysts in tuff range widely in size, but breakage is probably minor in low-explosivity deposits.

Some investigators explicitly noted that not all phenocrysts in tuffs are broken. Pirsson (1915, p. 200) wrote that, in addition to broken accidental crystalline material, tuffs contain juvenile crystals which can be “in places . . . strikingly perfect,” or which “may also be corroded, with deep embayments, the latter perhaps filled by glass.” Although he associated the cuspat e form of glass shards with expansion of gas bubbles in the melt, Pirsson did not explain the cause of “shattering of solid substances” in tuffs. Ross and Smith (1961) dealt at length with the glassy material in tuffs, but in only one brief paragraph (p. 35) did they consider phenocyst shapes, recognizing four types (our numbers in brackets): “The essential feldspar grains are [1] sharply euhedral in outline in a few tuffs, but more commonly they are [2] subhedral. Some show one side with a crystal face, and elsewhere show irregular or fractured edges. Other feldspar grains are [3] rounded or irregularly embayed . . . In some tuffs . . . there has been [4] extreme fracturing, so that most of the grains are sharply angular in outline.” Noble (1970) briefly noted the presence of euhedral phenocrysts in some Great Basin tuffs. These four investigators recognized the fact that broken phenocrysts are not always present in tuffs and that different phenocryst shapes exist which, by implication, originated by different, but unspecified, processes.

Over the past several years we have examined hundreds of thin sections of 117 cooling units and included cognate pumice clasts in the middle Tertiary ash-flow tuff province of the Great Basin, western United States (Best
et al., 1989). Significant differences in shapes of omnipresent feldspar phenocrysts can be categorized, following Ross and Smith (1961, p. 35), as (1) euhedral, bounded by planar crystal faces, (2) subhedral, possessing partial crystal faces or a somewhat irregular outline that is rectangular to triangular in overall shape, but ranging to anhedral, or lacking any regular shape, and (3) irregularly embayed, cuspat, resembling pieces of a jigsaw puzzle and some containing glass inclusions. Category (4), angular, of Ross and Smith (1961) was interpreted by them to be produced by “extreme fracturing.” We propose that the irregular shapes (3) represent crystals blown apart by expansion of melt within inclusions, whereas subhedral to anhedral feldspars (2), as well as angular grains (4), probably were derived by break-up of polygranular aggregates.

Our intent in this textural study is twofold. We plan to document shapes of felsic phenocrysts in Great Basin tuffs (e.g., Page and Dixon, 1994) and their cognate pumice clasts and to propose an origin for these contrasting shapes, beginning first with shapes whose origin is more certain followed by the more problematic and ambiguous phenocryst shapes. We aim to shed light on the general processes of “breakage,” “impact,” and “fracturing” of phenocrysts alluded to in published accounts of ash-flow tuffs. Such processes can provide insight into dynamics of volcanic eruptions that bear upon such widely ranging applications as climate change, volcanic hazards, magma genesis, and recognition and characterization of ancient ash-flow deposits and their related calderas and ore deposits.

EUHEDRAL PHENOCRYSTS

Some cooling units of ash-flow tuff in the Great Basin (Best et al., 1989) contain significant proportions of euhedral feldspar phenocrysts similar to those commonly seen in lava flows. Such tuff units include the rhyolitic Shingle Pass Tuff, Ryan Spring Formation, Escalante Desert Formation, and especially the Condor Canyon Formation (Fig. 1), many trachydacitic cooling units, and the crystal-rich dacitic Three Creeks Tuff Member of the Bullion Canyon Volcanics (Best and Grant, 1987). Euhedral plagioclases also occur in the crystal-rich Nugent Tuff Member of the Hu-pwi Rhyodacite (Fig. 2) in which the “plagioclase phenocrysts . . . are . . . surprisingly . . . little shattered and broken” (Ekren et al., 1980, p. 38). Many other cooling units contain euhedral phenocrysts mixed with other shapes.

There is no doubt that euhedral feldspar phenocrysts in a tuff represent well-formed intratelluric crystals that existed in the magma body prior to its explosive eruption which were not broken during eruption and placement of the pyroclastic flow. These euhedra presumably existed as free-floating, isolated crystals as well as grains in crystal-rich mush in marginal parts of the magma body.

EXPLOSION OF MELT-CONTAINING PHENOCRYSTS

Phenocrysts in all volcanic rocks—tuffs as well as lava flows—commonly contain glass inclusions. Sieve-textured plagioclase in intermediate-composition lava flows and embayed quartz in silicic rocks are particularly common and have been described and illustrated in numerous publications (e.g., Williams et al., 1982, Figs. 4-2A and 9-3C). Since 1989, laboratory investigations and theoretical analyses of melt inclusions have shown that they can fragment their host crystal during explosive eruptions, thus providing a mechanism for the breakage of phenocrysts. We first describe melt inclusions, then explain how they blow their host crystal apart, and finally show examples from Great Basin tuffs.

Melt Inclusions in Phenocrysts

Inclusions can form in at least two ways. First, skeletal crystals can trap pockets of melt (Roedder, 1979) during growth under high degrees of undercooling or supersaturation in the magma (e.g., Lofgren, 1980). Second, more slowly grown euhedral-faceted crystals can subsequently undergo partial resorption or corrosion under changing magmatic conditions, such as mixing with a compositionally different magma (Hibbard, 1981; Glazner et al., 1990) or decompression of the magma (Nelson and Montana, 1992). In thin sections of standard thickness it is difficult, if not impossible, to distinguish between a true inclusion, which is completely enclosed within the host crystal and most probably formed during skeletal growth or growth following partial resorption, and an apparent inclusion, which is an enlargement or corrosion channel extending inward from the margin of the crystal into the plane of the section from the third dimension. Sparse, more or less symmetric skeletal phenocrysts of quartz (e.g.,
All of the 117 tuff cooling units examined in the Great Basin contain plagioclase phenocrysts and, of these, 59% have at least some plagioclase with glass inclusions. Because inclusions commonly transect compositional zones and are generally irregular in outline and in arrangement within the crystal (Fig. 3), they apparently formed by partial resorption after initial growth, but entrapment as melt inclusions during skeletal growth cannot be ruled out with certainty.

Among the Great Basin cooling units that contain sanidine phenocrysts, only 16% have at least some sanidine with inclusions and small marginal embayments.

**Blown Apart Phenocrysts: Concepts**

Regardless of their origin, melt inclusions in felsic phenocrysts provide a means of fragmentation during explosive eruption and decompression of gas-charged magma. In relatively small, true-melt inclusions, the host crystal can be an effective, unfailing pressure vessel during even nearly isothermal explosive eruption as the pressure differential increases between the melt in the inclusion and the melt surrounding the host crystal (Lowenstein, 1994a). However, in a study of the Bishop Tuff, Anderson et al. (1989) and Anderson (1991, p. 536) found that some melt inclusions had burst their quartz phenocryst hosts while melt was still available to coat conchoidal fracture surfaces. In the conclusion of their study of tuffs at Crater Lake, Bacon et al. (1992, p. 1029) briefly referred to phenocrysts blown apart during eruption by vapor overpressure in melt trapped as inclusions. Tait (1992) calculated the coupled effects during magma ascent of the evolution of vapor pressure within a melt inclusion and the elastic deformation that the melt exerts on the host crystal. Melt inclusions are essentially unable to decompress significantly by expansion of the host crystal because of its relatively large elastic moduli, regardless of the chemical composition of the magma and its volatile species. So, as the ascending magma surrounding the crystal decompresses, the stress within the crystal in the neighborhood of the melt inclusion can exceed the tensile strength of the crystal, and it will crack. The cracking threshold decreases with increasing relative inclusion size because stresses are greatest in a narrow zone along the wall of the inclusion. Crystals containing many inclusions separated by relatively thin walls would be especially prone to breakage. Inclusions trapped at greater depth are more likely to blow apart upon decompression of the magma. Once the host crystal is cracked, the melt within the inclusion decompresses, volatiles exsolve, bubbles nucleate, expanding the inclusion further, and the crystal blows apart. Melt within hourglass inclusions connected through a narrow constricting neck to the melt surrounding the host crystal can partially decompress during eruption, but the crystal can still burst (Anderson, 1991).

Tait (1992, p. 154) also suggested that, because of the sluggish rate of exsolution of dissolved volatiles, melt inclusions in rapidly decompressed Plinian ejecta that rapidly quench in the turbulent cool atmosphere might have insufficient time to nucleate bubbles in the melt; crystals would not rupture. This suggestion was confirmed by Bacon et al. (1992, p. 1029), who found that only some of the inclusions in Crater Lake plinian deposits had ruptured their host, but all inclusion-filled crystals in subsequent co-genetic ash-flow deposits from the same magma system are broken. The same contrasts between Plinian and ash-flow deposits were recorded in other locales by Dunbar and Hervig (1992a, 1992b), Lowenstein (1994b, 1995), and Skirius et al. (1990). Moreover, it has been observed that bubbles in melt inclusions are smaller in plinian than ash-flow deposits (Dunbar and Hervig, 1992a; Lowenstein, 1993, 1995). As the ash-flow magma decompresses in its chamber during precursory Plinian eruptive activity, overpressured melt inclusions had more time after cracking of the host crystal to nucleate bubbles, expand, and blow it apart.
Blown-Apart Phenocrysts: Phenoclasts

Blown apart phenocrystal fragments, or phenoclasts, of plagioclase and quartz were found in more than 100 thin sections of the ash-flow tuff and hosted cognate pumice clasts of the Pahranagat Formation in the southern Great Basin (Best et al., 1995). Plagioclases in the pumice clasts contain numerous inclusions of vesicular glass. These significantly weakened crystals ruptured while still encased within the nonfragmented vesicular melt, because it is molded tightly around the disaggregated phenocrysts (Figs. 3 and 4). In phenocrysts that retain considerable regular external crystal form, phenoclasts shaped like pieces of a jigsaw puzzle have been displaced or jostled to create uneven optical extinction and faulted crystal margins surrounded by vesicular glass. Such phenocrysts were not ruptured by shear stresses in a flowing frothy melt because neither the crystal nor the host pumice show any indication of local flow, such as tubular vesicles. Rather, it appears conclusive that expansion of gas bubbles within the included pockets of melt ruptured the host crystals during decompression that accompanied eruption. Some plagioclase phenocrysts are so disrupted that it is impossible to reconstruct phenocrystals into an originally regular crystal form (Fig. 3C). In some pumice clasts, complete disaggregation occurred within a shearing froth so that the phenoclasts have been drawn out into lenticular aggregates within flow-foliated pumice.

Quartz phenocrysts in pumice clasts within the Pahranagat tuff show fragmentation similar to that of plagioclase, but the quartz phenoclasts are different because the shape, size, and spacing of the inclusions and embayments in quartz are different (Fig. 4). The photomicrographs show that the quartz phenocrysts ruptured while enclosed within the vesicular melt and not during subsequent fragmentation and flow of the vesiculating magma. However, because the inclusions and/or embayments tend to be relatively larger and more widely spaced than in plagioclase, as few as two or three phenoclasts were created from one crystal.

Prior to eruption, the Pahranagat magma decompressed by as much as 4–5 kbar, on the basis of Al concentrations in zoned amphibole phenocrysts (temperature-corrected pressures; Christiansen and Best, unpublished data). This 15–19 km ascent in the magma system may have intensely corroded both the plagioclase and the quartz phenocrysts, creating abundant melt-filled embayments. Fragmentation of the vesiculating melt and of phenocrysts of plagioclase and quartz, like those illustrated in Fig-
ures 3 and 4, during eruption and dispersal of the Pahranagat ash flow would have produced ash-size vitroclasts and phenocrysts. Ash-flow tuffs of the Pahranagat Formation contain such phenocrysts (Fig. 5).

At least some of the plagioclase grains in 68 of the other 116 middle Tertiary tuff cooling units in the Great Basin have jigsaw-puzzle shapes similar to those in the Pahranagat tuff. One of these cooling units, the Blue Sphinx Tuff, was noted by Ekren et al. (1980) to contain intensely resorbed quartz phenocrysts; like the Pahranagat, the Blue Sphinx also contains abundant small phenocrysts of plagioclase and quartz (Fig. 6), together with zoned amphiboles, the Al concentrations of which record 3–4 kbar of magma decompression prior to emplacement. Original phenocrysts of plagioclase and quartz in the Pahranagat and Blue Sphinx tuffs are among the most inclusion-rich of any cooling units in the Great Basin; they also contain amphiboles known to be strongly zoned in Al concentration. Further study is needed to determine what role, if any, the apparently large decompressions in silicic magmas play in the development of abundant melt inclusions in plagioclases that are subsequently blown apart. Dissolved water concentrations in the melt inclusion are certainly important and, at the possibly greater depths of entrapment implied for the Pahranagat and Blue Sphinx magmas, concentrations could have been greater, allowing for more efficient rupturing of hosts’ crystals.

Many tuff cooling units in the Great Basin (e.g., Fig. 7) contain larger phenocrysts of quartz and smaller of plagioclase in which inclusions are more closely spaced, as is the case in the Pahranagat tuff. Contrasts in shapes, as well as sizes, of plagioclase phenocrysts are evident in some tuffs; where inclusions are elongate as well as closely spaced (Fig. 8), many corresponding phenocrysts are elongate, compared to the more commonly equant phenocrysts in Figures 5–7. Many tuff cooling units that have phenocrysts of plagioclase also host cognate pumice lapilli which contain variably disaggregated, inclusion-filled plagioclase phenocrysts similar to the phenocrysts (Fig. 9). Such paired samples of the initial, unfragmented magma and the erupted pyroclastic material lend strong support to the concept that inclusion-filled phenocrysts blow apart during explosive eruption. Several other examples of felsic phenocrysts are obvious in the photomicrographs in Ross and Smith (1961, Figs. 17, 21, 34, 36, and 38).

Phenocrysts of sanidine are rare in Great Basin tuffs, reflecting the fact that sanidine phenocrysts contain few melt inclusions.

In contrast to ash-flow tuffs, felsic phenocrysts in lava flows are rare. In thin sections of 110 andesitic and rhyolitic Tertiary lava flows in the Great Basin only a few phenocrysts were found among thousands of felsic phenocrysts, many of which contain melt inclusions. The relatively slow rate of extrusion of lava flows apparently allows differential reequilibration of volatiles, chiefly H₂O, between the melt inclusion and melt surrounding the crystal. Qin et al. (1992) found that less than 2 yr are required for H₂O in a 50-µm-diameter inclusion of rhyolitic melt at the center of a 2-mm-diameter quartz crystal to reach 95% reequilibration with external melt at 800 °C. High-temperature annealing of cracks or ductile deformation of the host crystal during the slow extrusion may also play a role.

PHENOCRYS STS BROKEN BY IMPACT

Fragmentation of phenocrysts by collisions of juvenile crystals with one another, or mutual impact, in pyroclastic eruption columns and ensuing ash flows has been implied by some geologists (e.g., Fisher and Schmincke, 1984, p. 105). Impact breakage of crystals rendered weaker because of melt inclusions could occur in the pyroclastic milieu; however, this cannot be the only mechanism for creation of phenocrasts, because they are found in pumice where impact did not happen. If mutual impact is a viable general mechanism, crystal-rich tuffs might be expected to contain more impact-fragmented phenocrysts than crystal-poor tuffs. However, this does not seem to be the case in Great Basin tuffs, because some crystal-rich tuffs contain abundant euhedral phenocrysts of feldspar. One can calculate the statistical probability of one-time mutual impact between crystals in a milieu of an infinitely large number of similarly sized crystals and vitroclasts. In an ash flow containing 50% vitroclasts and 50% crystals, the upper limit of phenocryst concentration in Great Basin tuffs, 25% of the mutual impacts are between crystals. For 30%–20% crystals, which is a more common range of concentration, 9%–4% of the impacts are between crystals. In the case of 10% crystals, found in many tuffs, only 1% of the theoretical impacts are between crystals. If pyroclastic flows move by laminar rather...
than turbulent flow (e.g., Francis, 1994, p. 217), then neighboring particles move at about the same velocity and the probability of forceful collisions between crystals is minimal. Another significant factor reducing the probability of effective impact fracturing of phenocrysts is the fact that the crystals in expanding gas-charged magmas are coated with films of vesicular glass or melt (Fisher, 1963; Anderson, 1991). Such coatings would absorb to some degree the force of mutual impact.

Experiments

We have not attempted the difficult task of trying to experimentally simulate fragmentation of phenocrysts by mutual impact in a fast-moving mixture of vitric particles and crystals. However, some insights into fragment shapes were found by high-speed impact of plagioclase grains against a stationary, polished slab of syenite at room temperature. The impacted grains were diamond-sawed rectangular parallelepipeds of unfractured plagioclase that contained no glass inclusions. Two sizes of grains were impacted in 150 trials. The first were grains weighing 0.04–0.07 g, averaging 0.05 g, and measuring 2–4 mm along an edge. The second were grains weighing 0.02–0.04 g, averaging 0.025 g, and measuring 1–3 mm along an edge. Each grain before impact and all fragments recovered after impact were examined with a binocular microscope to ascertain results.

Larger grains were impacted at speeds of 15 to 30 m/s by using a table-mounted slingshot. Such velocities lie in the lower range of published pyroclastic flow velocities (9–134 m/s or 32–482 km/hr according to Moore and Melson, 1969; Fisher and Schminke, 1984, Table 8-1; Rowley et al., 1981; Taylor, 1958; Bullard, 1984; but 150–300 m/s according to Wilson, 1985). For six grains impacted at 15 m/s, typical results were either that the...
In summary, breakage by mutual impact of inclusion-free plagioclases at low velocities of 15 m/s mostly produces dust-size pieces chipped off the edges and corners of the rounding parent grain, reminiscent of wind-blown sand grains. Slightly greater velocities can yield substantial breakage, but generally only after repeated impact, as could occur in a turbulent ash flow. Significant fragmentation occurs on first impact at 30 m/s for larger grains but only for about half the smaller grains. Impact breakage of still smaller grains, <1 mm, would presumably require greater velocities.

In other impact experiments, plagioclase grains were loaded into a shotgun shell in lieu of “shot” and propelled with a speed of about 1000 m/s into the stationary syenite slab. Recovery of impacted grains was less complete, but thin sections of fragments revealed shapes (see next section) similar to those produced at lower speeds from the slingshot.

If phenocryst shapes in ash-flow tuffs originated by impact fracturing, comparative size distribution analysis (e.g., Hartmann, 1969) of fragments generated in these experiments with phenocrysts in tuffs might provide evidence for phenocryst impact in the latter. However, because of differential winnowing, or elutiation, of finer particles, including small crystal fragments from a pyroclastic flow during its eruption and dispersal (e.g., Sparks and Walker, 1977), the validity of such a comparison would be limited. Elutiation would also invalidate direct comparison of phenocrysts in a sample of tuff and its included cognate pumice, in which no impact occurred.

Shapes of Plagioclase Fragments Produced by Impact

Plagioclase fragments produced by impact were embedded with random orientations in epoxy cement on a glass slide. Thin sections allowed direct comparison with shapes of phenocrysts in tuffs. About half of the fragments are blocky cleaved pieces that appear as more or less regular rectangular or triangular shapes in thin section; these are similar to the shapes of many of the crystals in tuffs. Other fragments of impacted plagioclase commonly have one or more stepped outlines governed by the (010) and (001) cleavages. More significant shapes are related to curved, stepped ribs on conchoidal fractures. In the two dimensions of a randomly oriented thin section, these ornamented fractures create bizarre shapes (Fig. 10); these include deep linear reentrants grading into slender fragments, two or more of which, though appearing separate and independent in the plane of the thin section, are actually ribs of one grain, as revealed by a common optical orientation. Continued impact would tend to obliterate some of the sharply angular and more delicate features, which, however, are more robust in three dimensions.

If impact fragmentation had generally occurred in Great Basin ash flows, the shapes displayed in Figure 10 would be more common. However, of the hundreds of thin sections of Great Basin tuffs we have examined, such shapes are virtually nonexistent in feldspars but have been noted in rare quartz; the upper member of the tuff of Ryecroft Canyon (Fig. 11) contains some stepped boundaries. Melt coatings on phenocrysts would certainly inhibit breakage by mutual impact, and so too would laminar flow. The occurrence of euhedral, unbroken phenocrysts in some tuffs (Figs. 1 and 2) indicates that factors which produce breakage independent of rupturing related to melt inclusions have not been significant.

Aside from production of phenocrysts as detailed above, other processes could produce fragmented phenocrysts. Fractured xenocrysts might be
It may be assumed that aggregates bear a cognate relationship to discrete anhedral to subhedral phenocrysts in the same tuff sample; that is, all crystals formed in the same magma. This was tested for the Nugent Tuff Member (Fig. 2) by electron microprobe analysis (Fig. 12) of the three textural types of plagioclase-composite grains, discrete subhedral-anhedral phenocrysts, and discrete euhedral phenocrysts. All three have the same compositional range, suggesting that free-floating discrete crystals and crystals separated from aggregates during eruption were derived from the same magma.

Disintegration of aggregates could occur in three ways. First, interstitial melt trapped between overgrowing grains could vesiculate and blow the aggregate apart during rapid decompression as the magma was explosively erupted, as is the case for isolated single phenocrysts that contain melt inclusions. Nakada et al. (1994) found such glass-bearing aggregates to be common in pre-Mazama rhodacitic lava flows at Crater Lake. Aggregates consisting of as many as 12 or so crystals are widespread in Great Basin.

Figure 10. Cross-polarized light photomicrographs of experimentally impacted plagioclase fragments produced at a velocity of 30 m/s. Bizarre two-dimensional shapes are a consequence of curved fracture surfaces ornamented with stepped ribs that are controlled in part by two intersecting cleavages. Apparently separate plagioclases in each photomicrograph are all optically continuous and compose one intact fragment. Note intricate serrations and steps on fragments in (A) and (B) (ignore numerous air bubbles in mounting cement). Scale bars are 0.5 mm.

Figure 11. Upper member of the tuff of Ryecroft Canyon collected near the mouth of Meadow Creek in the Toquima Range about 6 km north of Belmont, Nevada, sample CORC-1B. Two labeled plagioclases (P) show shapes not unlike those produced experimentally by impact (see Fig. 10). Large subhedral sanidine (S) has parts plucked out during processing of thin section and is not like impacted feldspar fragments. Scale bar is 0.5 mm.

broken from wall or roof rocks during explosive eruption. However, xenocrysts appear to be rare in middle Tertiary Great Basin tuffs which we have examined. In contrast, for example, our few samples of the Quaternary Bishop Tuff, which vented partly through granitic rock, contain obvious felsic xenocrysts marked by multiple sets of healed microfractures typical of plutonic feldspars.

PROBABLE ORIGIN OF SOME SUBHEDRAL TO ANHEDRAL PHENOCRYSTS

Superficially, some shapes of subhedral grains resemble those produced by impact breakage. For example, phenocryst W in the upper center of Figure 1B is a slender plagioclase grain, not unlike that shown in Figure 10 (C and D), but lacking sharply angular steps. However, just below and to the left is an aggregate of plagioclase that contains grain X, which is similar in shape and size to grain W. Also in Figure 1B, in the lower left, is a subhedral plagioclase grain Y that has perhaps three regular crystal faces and an irregular fourth side which, conceivably, could be the result of impact fracture. However, to its right is another aggregate of plagioclase that has a grain Z, similar to Y. Additional examples of the similarity in shape and size between discrete grains and grains in aggregates can be found by careful examination of Figures 1B and 2B. Such similarities can also be found in numerous other Great Basin cooling units. Thus, disintegration of aggregates can at least contribute to the population of isolated subhedral to anhedral grains in ash-flow tuffs, as Nakada et al. (1994) found in pre-Mazama lava flows at Crater Lake.

Some of the peripheral crystals in aggregates have euhedral external margins, whereas internal margins are generally not euhedral. All margins of embedded grains in clots tend to be subhedral to anhedral, similar to crystals in a holocrystalline plutonic rock. Aggregates can develop in crystallizing magma by nucleation of a crystal on the surface of another crystal, or as independent crystals grow and drift together, to become permanently attached. Continued growth of these attached crystals create mutually interfering, common grain margins that are not perfectly euhedral (Vance, 1969, p. 24; Bryon et al., 1994). Phenocrysts described by Ross and Smith (1961, p. 35) as “subhedral . . . one side with a crystal face, and elsewhere show irregular or fractured edges” may have originated by freeing peripheral crystals from an aggregate, rather than by impact fragmentation of discrete phenocrysts.

It is also possible that aggregates form due to the interaction of melt and a melt inclusions. Nakada et al. (1994) found such glass-bearing aggregates to be common in pre-Mazama rhodacitic lava flows at Crater Lake. Aggregates consisting of as many as 12 or so crystals are widespread in Great Basin.
tuffs, but only 2 have been found that contain glass (Fig. 13). Generally, melt-bearing aggregates hosted within tuff would be expected to have been blown apart during explosive eruption, rather than commonly retaining their integrity as in more slowly extruded lava flows. Thus, only melt-free clots would generally survive during the rapid decompression accompanying explosive eruption. Second, some holocrystalline aggregates could break apart by impact in the pyroclastic flow. Although we find little evidence for fracture of discrete phenocrysts by impact, larger aggregate masses would have greater momentum at a given velocity and could break apart on collision. Third, grains in aggregates might break up by differential expansion of the randomly oriented, low-symmetry grains during the rapid decompression of the exploding magma. It is not unlikely that two or more of these three mechanisms could conspire in explosively erupting magmas.

We have not attempted an analysis of crystal size distribution (Cashman and Marsh, 1988) in these tuffs to ascertain whether the phenocrysts have a magmatic growth signature. Preferential elutriation of fine particles, including smaller phenocrysts and phenoclasts, from the pyroclastic material during eruption and dispersal would distort any pristine magmatic size distribution.

SUMMARY AND GEOLOGIC IMPLICATION

Shapes of felsic phenocrysts in Great Basin tuffs can be classified into three basic categories, each created by a different process. The first category includes euhedral grains, bounded by planar crystal faces. These originated as unbroken, free floating crystals in the preeruption magma; they indicate conclusively that not all intratelluric crystals are broken in ash-flow tuffs. The second category is made up of subhedral to anhedral grains, possessing only partial or no bounding crystal faces. The origin of this shape is problematic. Many may be disaggregated polygranular crystalline material. Few were possibly formed by mutual impact. Some may originate in the manner of the next category. The third category is the phenoclasts, which are cuspat, embayed fragments of phenocrysts that contained melt inclusions. Textural observations presented here provide convincing evidence that inclusion-filled phenocrysts rupture within vesiculating rhyolitic melt prior to fragmentation of magma. As decompressing magma blows apart into pyroclasts during explosive eruption, phenoclasts become part of the ash-size ejecta along with vitroclasts.

Although some tuffs in the Great Basin contain felsic phenocrysts shaped by a single process, the majority are likely polygenetic. Most originated by fragmentation of crystals containing melt inclusions and by breaking apart aggregates.

Hence, both melt and many crystals in ash-flow eruptions are blown apart in response to decompression and vesiculation of melt, yielding, respectively, vitroclasts and phenoclasts. Vesiculation of melt in a magma body and of melt inclusions in a crystal are analogous processes that operate on vastly different scales. Vesiculation of a magma body accompanies decompression and communication with atmospheric pressure, locally by breaking through the containing roof rock, leading to fragmentation of the body and production of pyroclasts. Vesiculation of melt inclusions also ac-
companies decompression, causing the host crystal to fragment into phenocrysts.

The origin of crystal shape in ash-fall tuffs depends upon crystal phase. Thus, quartz virtually always has embayments and inclusions of melt so that phenocrysts, both arcuate slivers and embayed anhedral, occur in all quartz-bearing tuffs. All tuff units contain plagioclase and in more than half of them some plagioclase occurs as phenocrysts. Widespread feldspathic aggregates are matched by equally widespread anhedral to subhedral phenocrysts of feldspar. Sandine in most tuffs is the most free of inclusions of the three felsic phases, is usually subhedral to euhedral, and probably was derived from breakup of aggregates and from free-floating euhedral crystals.

Obliteration of the diagnostic vitroelastic and eutaxitic matrix textures in some ash-fall tuffs by secondary flow after emplacement (rheomorphism) or by devitrification through hydrothermal alteration or metamorphism has made positive recognition difficult or equivocal. For example, Henry and Wolff (1992) reviewed the difficulties of interpreting the mechanism of emplacement of large bodies of high-temperature silicic volcanic rock in Africa, Australia, and North America. They indicated that "broken phenocrysts ranging widely in size" is one of several characteristics of conventional ash-fall tuffs. However, our investigation of shapes of felsic intratelluric grains in Great Basin ash-fall tuffs has shown that phenocrysts are widespread. In contrast, felsic phenocrysts are rare in lava flows and absent in Plinian fall deposits. These contrasts apparently are controlled by kinetic factors, as suggested by Tait (1992, p. 154). Rapidly erupted Plinian pyroclasts that form ash-fall deposits mix with cool atmosphere and thus generally quench before volatiles dissolved in melt inclusions can nucleate bubbles and blow their host crystals apart. Explosive eruption of pyroclastic flows commonly follows precursory Plinian activity, so melt inclusions have some time to vesiculate in the magma chamber after its initial opening; eruption of the heat conserving flow allows additional opportunity for bubble growth in melt inclusions and rupturing of the host crystal. Relatively slower extruded lava flows have few phenocrysts, for possibly two reasons. Diffusive reequilibration of volatile pressure in melt inclusions with melt surrounding host crystals precludes rupturing overpressures. Also, during slow extrusion cracked or ductily deformed crystals may anneal. Euhedral, subhedral, and anhedral phenocrysts can be found in any volcanic rock and are therefore not diagnostic of a particular mode of emplacement.

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