

SUMMARY FOR CASCADE VOLCANOES FIELD TRIP

MIXING AND VOLATILES IN SOUTHERN CASCADE RANGE MAGMAS

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Young eruptive sequences at Lassen Park, Medicine Lake, and Crater Lake provide direct evidence for replenishment of crustal magma reservoirs by primitive magma from the mantle, and for the development of water-rich caps on these reservoirs. Evidence for injection of basaltic magma into silicic magma reservoirs, with subsequent mixing, is provided by the disequilibrium phenocryst assemblages and abundant inclusions of mafic foam which characterize these rocks.¹ In response to injection into cooler silicic magma, basaltic magma undergoes rapid crystallization and vesiculation, forming a foam consisting dominantly of acicular plagioclase and hornblende or pyroxene, interstitial silicic melt, and bubbles. Bubble growth so lowers the bulk density of these "pillows", that their bulk density is always lower than their nonvesicular host lavas.² This suggests that mixing is driven by the buoyant rise of basaltic material within the reservoir. For this to be the case, the reservoirs must be within ~ 10 km of the surface. Deeper silicic magma systems and/or drier basaltic magma would undergo strictly bimodal evolution (i.e., little or no chemical interaction between primitive and reservoir magma).

Heating of the reservoir by cooling and crystallization of the injected basalt causes resorption and/or reaction of crystals in the reservoir magma. The extent of these effects depends both on the position of crystals relative to hot basalt at the time of injection, and the volume of basalt injected relative to the volume of the reservoir.

In general, basalt injection is followed by a period of convective stirring, during which time the magma becomes more homogeneous through disaggregation and dispersal of the mafic foam, and crystalline phases grow which are appropriate to the new temperature and composition of the system. Chemical disequilibrium is preserved within crystals and between melt trapped in crystals and the host melt, but not between melt and the outer few μm 's of crystals or within the melt phase, except for magma erupted explosively immediately after basalt injection. Zoning patterns produced in plagioclase crystals during mixing are preserved even in the completely crystallized plutonic equivalents of these rocks.

Because of the extremely slow rate at which bubbles could rise or volatiles diffuse in silicic melt relative to eruptive time scales, bubble-free silicic materials which have cooled during eruption must preserve preeruption magmatic volatile contents. Although commonly interpreted as accidental lithic fragments, bubble-free obsidian clasts in Plinian air fall deposits contain an order of magnitude higher volatile content and far fewer microlites than obsidian from flows.³ But like obsidian from flows, the clasts release their volatiles at high temperature, indicating that the volatiles are structurally bound in the glass and therefore are magmatic. The clasts tend to be concentrated in the upper

portion of tephra layers, suggesting a deeper origin relative to pumice, the dominant component of these deposits. Restricted occurrence of volatile-rich obsidian to small (< 1 cm) clasts and thin (< 1 cm) rinds on larger clasts, together with its microlite-poor character, indicates that the obsidian is a product of rapid quenching of initially vapor-undersaturated volatile-rich magma. The clasts thus provide a direct means for determining preeruption volatile contents of explosively erupted magmas.

Analysis of obsidian clasts in tephra at Medicine Lake and Crater Lake (and Inyo Domes) indicate that small to moderate volume (10^{-3} to 10^{-1} km³) Plinian eruptions are driven by 0.5 to 1.0 wt.% volatiles, consisting dominantly of H₂O with minor CO₂ and trace amounts of HF and HCl, but no S-bearing species. The observed water contents require that vesiculation occurs within 300 m of the surface, and therefore must take place in the conduit rather than in the reservoir.

In the eruptive sequences studied, multiple Plinian eruptions were followed by extrusion of flows. The abrupt change from 0.5-1.0 wt.% H₂O in the tephra eruptions to 0.1 wt.% H₂O in the flows implies strong stratification of the magma body, with water-rich magma overlying nearly anhydrous magma. This stratification probably results from the effect of H₂O on melt density. Absence or scarcity of mafic inclusions in the tephra can be attributed to the lower density of magma comprising the water-rich cap, preventing rise of inclusions into this region. Variation in water content within these reservoirs does not appear to be accompanied by significant variation in other volatile components. Unless these magmas have somehow degassed prior to eruption, which seems unlikely, their relatively low water and crystal contents require very high temperatures within the reservoirs, probably well in excess of 1000°C.

Since lavas and tephra similar to those described here have erupted repeatedly from nearby vents, it appears that magma reservoirs beneath these volcanoes are long-lived features which receive episodic injections of basalt and become strongly stratified in water content before eruption. If so, then the mixing events do not irreversibly contaminate the reservoir, nor do explosive eruptions permanently deplete the source of magmatic water. Possible sources of the water include degassing of the basalt (although this seems inconsistent with the absence of S in the tephra) and inward diffusion from the walls of the reservoir.

This field trip will provide an opportunity to examine hybrid and associated nonhybrid eruption products of magmatic systems in which the crystal content of the reservoir magma varies from 0 to 30 vol.%, the volatile content of the reservoir magma varies from 0.1 to 1 wt.%, the proportion of basaltic to silicic magma in mixtures varies from $< 1:10$ to $1:1$, and the reservoir residence time between basalt injection and eruption varies from short to long.

Lassen Volcanic National Park

Young lavas of the Lassen area represent mixtures of varying proportions of basaltic magma with relatively crystal-rich rhyolitic magma, withdrawn from a single large reservoir or multiple smaller reservoirs containing similar rhyolitic magma.⁴ These lavas are the rhyodacite to dacite domes of Chaos Crags and Lassen Peak, the dacite tephra, flow, and plug of the 1915 Lassen

summit eruption, the andesite flow at the saddle between East and West Prospect Peak, and the 1851 Cinder Cone and flow. The dome lavas are of special interest because of their close petrologic resemblance to granodiorite of coastal batholiths. These post-glacial domes were extruded through a glacially polished base of petrologically similar flows.

Prior to the mixing events which produced these lavas, the parent rhyolitic magma or magmas contained An₃₀ plagioclase and quartz. Based on data from Chaos Crags, biotite was also present and crystal content of the rhyolitic magma was ~ 30 vol.%. Batches of basaltic magma injected into the reservoir contained < 5 vol.% crystals consisting of An₈₀₋₉₀ plagioclase, Fo₈₀ olivine, and aluminous augite.

Chemical effects of mixing increase with the proportion of basalt admixed. In the Chaos Crags lava where the basaltic component is < 20 wt.%, reequilibration of reservoir-derived phenocrysts is largely limited to reverse zoning on sodic plagioclase and mild resorption of quartz, although phenocrysts engulfed by inclusions show more severe effects. Some inclusions exhibit an outer mixed rind in which these reservoir-derived phenocrysts occur. In these cases, plagioclase has undergone partial melting, quartz has reacted with melt to form pyroxene, and biotite has reacted to hornblende + plagioclase + magnetite + melt. In the 1915 dacite, which appears to contain ~ 30 wt.% basaltic component, all An₃₀ plagioclase grains are enclosed by partially melted plagioclase consisting of skeletal calcic plagioclase and glass, and quartz grains show strong resorption. In the Prospect Peak andesite, which appears to contain ~ 50 wt.% basaltic component, partial melting of some An₃₀ plagioclase grains has entirely destroyed the sodic core, all quartz grains have well-developed pyroxene jackets, and some quartz grains have completely reacted to form clots of pyroxene in glass. Although the reservoir-derived phenocrysts contain inclusions of rhyolitic glass, these inclusions become increasingly contaminated due to melting of the host crystal as the basaltic component of the mixture increases.¹

Mafic inclusions are largest and the host least contaminated with basaltic debris in the rhyodacites, while the reverse is true of the andesites. This presumably reflects the less favorable conditions for rapid crystallization of basalt and the more favorable conditions for disaggregation and stirring where the proportion of injected basalt is large. In the rhyodacitic to dacitic dome magmas, chilling of basalt produced inclusions with strongly zoned plagioclase (An₇₅₋₄₀), hornblende (zoned from low Si and high Na+K to high Si and low Na+K), and augite (zoned from high Al to low Al). Chilled and crenulate margins are relatively common in inclusions in the domes, especially Lassen Peak. In the more mafic mixtures, pyroxene occurs in place of hornblende in the inclusions. An inclusion from Chaos Crags has a grain density of 2.76 g/cm³ and a bulk density of 2.16 g/cm³, while vesicle-free dacite has a density of 2.47 g/cm³.² Mafic inclusions are scarce in the tephra associated with Chaos Crags, except for the final tephra erupted.

Considerable crystallization occurred in the dome magma following basalt injection, with growth of unzoned high Si, low Na+K hornblende and An₄₀ plagioclase, and was accompanied by dispersal of basaltic debris. Although chemical equilibrium was achieved within the melt phase in all these lavas, disequilibrium within the melt is preserved in the 1915 tephra, apparently because of an unusually short time span between basalt injection and eruption.

Medicine Lake Highland

The Glass Mountain flow on the Medicine Lake Highland provides perhaps the most instructive example of magma mixing, because the entire range of lithologies from uncontaminated rhyolite to well-mixed dacite are present within this single eruptive unit.⁵ Prior to mixing, the rhyolitic reservoir magma contained no crystals while the basaltic magma contained Fo₈₀ olivine, An₇₅ plagioclase, and Wo₄₁En₄₃Fs₁₆ augite. After basalt injection, reversely zoned En₆₅₋₇₆ orthopyroxene and An₄₆₋₅₁ plagioclase grew concurrently with extensive contamination of the host magma through disaggregation of the mafic inclusions. The basaltic component in the lavas ranges from 0 to 25 wt.%, with the most mafic lava erupted first, a zonation which supports the hypothesis that mixing is driven by vesiculation and flotation of the basaltic material. The inclusions, which consist dominantly of plagioclase and pyroxene, have a grain density of $2.79 \pm 0.01 \text{ g/cm}^3$ and a bulk density of $2.15 \pm 0.04 \text{ g/cm}^3$, while density of the host lava ranges from $2.38 \pm 0.01 \text{ g/cm}^3$ (rhyolite) to 2.55 g/cm^3 (dacite).⁶

Mafic inclusions are absent from the tephra erupted prior to extrusion of Glass Mountain. Obsidian clasts in the tephra, which represent almost perfectly quenched samples of hydrous rhyolitic magma, reach concentrations as high as 55 wt.% at the top of tephra layers.³ This observation, together with other indications of the relative slowness of bubble nucleation and growth in rhyolitic magma, implies that the rate of eruption of vesiculated magma exceeded the rate of generation of vesiculated magma, and that eruptions terminated when the vesiculated magma was exhausted. Average water contents of clasts from the upper four layers range from 0.5 to 0.9 wt.%. Based on these water contents, most bubble growth occurred within 300 m of the surface. However, some obsidian clasts contain small CO₂-rich bubbles, which could have formed at greater depth since CO₂ is relatively insoluble in melt at low pressure. The Glass Mountain tephra/lava sequence is thus interpreted as a consequence of the upward flow of magma vertically zoned in water content. Water-rich magma erupted in pulses, with vesiculation occurring during brief repose periods and vesiculated magma ejected in each explosive event. This was followed by quiet extrusion of nearly anhydrous magma as the flow. Water content of magma which produced the flow is so low ($0.10 \pm 0.04 \text{ wt.}\%$) that only the upper 5-10 m ($P=1-2 \text{ bars}$) vesiculated.

Crater Lake

The portion of the Glass Mountain flow which contains a small basaltic component closely resembles the late precaldera Llao Rock rhyodacite flow at Crater Lake. This flow contains ~ 10 vol.% plagioclase, minor pyroxene and oxides, and mafic inclusions consisting dominantly of plagioclase and hornblende. Prior to mixing, the basaltic magma contained phenocrysts of Mg-rich olivine, calcic plagioclase, and hornblende. The silicic magma either lacked crystals prior to mixing, or the proportion of injected basaltic magma was insufficient to cause resorption of the crystals it contained. The mafic inclusions have a grain density of 2.79 g/cm^3 , a bulk density of $1.87 \pm 0.03 \text{ g/cm}^3$, and the host lava has a density of $2.38 \pm 0.01 \text{ g/cm}^3$.²

Obsidian clasts in tephra underlying the flow average close to 0.7 wt.% H₂O through much of the deposit, but drop to 0.40 ± 0.09 wt.% in the final tephra.³ Mafic inclusions are present but scarce in the tephra.

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6. Eichelberger, J. C., U. S. Geological Survey Circ. 838, 183-189 (1981).

Copies of 1-4 and 6 are attached.