Is the Valles caldera entering a new cycle of activity?

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ABSTRACT

The Valles caldera formed during two major rhyolitic ignimbrite eruptive episodes (the Bandelier Tuff) at 1.61 and 1.22 Ma, after some 12 m.y. of activity in the Jemez Mountains volcanic field, New Mexico. Several subsequent eruptions between 1.22 and 0.52 Ma produced dominantly high-silica rhyolite lava domes and tephras within the caldera. These were followed by a dormancy of 0.46 m.y. prior to the most recent intracaldera activity, the longest hiatus since the inception of the Bandelier magma system at ~1.8 Ma. The youngest volcanic activity at ~ 60 ka produced the SW moat rhyolites, a series of lavas and tuffs that display abundant petrologic evidence of being newly generated melts. Petrographic textures conform closely to published predictions for silicic magmas generated by intrusion of basaltic magma into continental crust. The Valles caldera may currently be the site of renewed silicic magma generation, induced by intrusion of mafic magma at depth. Recent seismic investigations revealed the presence of a large low-velocity anomaly in the lower crust beneath the caldera. The generally aseismic character of the caldera, despite abundant regional seismicity, may be attributed to a heated crustal column, the local effect of 13 m.y. of magmatism and emplacement of mid-crustal plutons. Seismic signals of magma movement in the deep to mid-crust may therefore be masked, and clear seismic indications of intrusion may only be generated within a few kilometres of the surface. We therefore encourage the establishment of a local dedicated volcanic monitoring system.

INTRODUCTION

The Valles caldera is the type example of a resurgent caldera (Smith and Bailey, 1968). It has long been recognized that the caldera complex went through at least two major ignimbrite cycles (Smith and Bailey, 1966). Little is known or understood about the onset of identifiable eruptive cycles associated with calderas, because the early products of an active cycle may be obscured or destroyed by climactic events. How such cycles begin bears on the questions of how bodies of caldera-forming ash-flow magma are generated, and identification of areas at long-term risk of major eruption. In this paper, we present data suggesting that the youngest eruptive products of the Valles caldera represent a new magma batch, independent of earlier systems developed on the same site. We take the position that the timing and character of the most recent volcanic products from the Valles caldera, in the light of geophysical considerations, may signal the onset of a new active cycle.

VOLCANIC HISTORY

The Jemez Mountains volcanic field is a sprawling edifice of 2000 km^3 with indications of activity stretching back to at least 13 Ma; most of its history is dominated by mafic to intermediate volcanism (Smith et al., 1970; Gardner et al., 1986). The first 11 m.y. of activity built a large volcanic ridge on the western margin of the Rio Grande rift. The isotopic compositions of these lavas record extensive interaction between mantle-derived magmas and local Proterozoic crust throughout this period (DePaolo et al., 1992). At around 1.8 Ma, central activity became exclusively rhyolitic, and there was eruption of high-silica rhyolitic ignimbrites, having strong chemical affinities to the Bandelier Tuff, from the future site of the Valles caldera (Spell et al., 1990). The first major episode of caldera formation at 1.61 Ma accompanied the eruption of the Otowi Member of the Bandelier Tuff. Subsequent activity produced intracaldera high-silica rhyolite domes and associated tuffs (Smith et al., 1970). At 1.22 Ma (Izett and Obradovich, 1994), the Tshirege Member of the Bandelier Tuff erupted to form the Valles caldera on approximately the same site as the earlier structure (Self et al., 1986). Resurgent uplift of the central part of the Valles was accompanied and followed by the eruption of rhyolitic lavas onto the caldera floor up to the late Quaternary (the Valles Rhyolite; Smith et al., 1970). Chemically and temporally, the caldera-related rhyolites fall into several groups. Each of the two members of the Bandelier Tuff and the temporally associated precursor and successor minor lavas and tuffs forms a distinct but chemically consanguinous group. Spell et al. (1993) showed that the postresurgence Valles Rhyolite units (Fig. 1) are themselves the products of four magma batches separated by significant time intervals; the youngest batch produced the southwestern moat rhyolites, a series of lavas and pyroclastic deposits (Fig. 1). These rocks are petrologically and geochemically dissimilar to all earlier caldera-related units. A hiatus of 0.46 m.y. preceded this youngest activity, by far the longest since the inception of exclusively rhyolitic activity at ~1.8 Ma.

SOUTHWESTERN MOAT RHYOLITES

The term SW moat rhyolites is used to collectively denote the El Cajete, Battleship Rock, and Banco Bonito Members of the Valles Rhyolite Formation (Smith et al., 1970), and the VC-1 rhyolite lava of Goff et al. (1986). These units and their vents are found in the southwestern sector of the Valles caldera moat, between the caldera wall and the resurgent dome (Fig. 1). They are petrologically distinct from the preceeding high-silica rhyolite domes of the Valle Grande Member (Fig. 1) in consisting of 72%–73% SiO_2 rhyolite, with very distinctive disequilibrium relations among phenocrysts.

Eruption Chronology

Self et al. (1991) considered the three SW moat rhyolite members to be the related products of two eruptions. Our work on newly available exposures suggests that the whole sequence is the result of a lengthy episodic eruption, which consisted of at least three phases of lava extrusion, each preceded by pyroclastic activity.

Initial Plinian falls were dispersed southeast of the vent, and were accompanied by minor pyroclastic surges and flows. This phase was followed by a hiatus in explosive activity during which a lava dome grew in the vent; this dome was destroyed during subsequent explosions and was the source for abundant cognate vitrophyric fragments during the second phase. Fallout was dispersed to the south during this phase, accompanied by numerous and relatively voluminous pyroclastic flows. Several of these flows ponded in San Diego Canyon to form the Battleship Rock ignimbrite. This phase ended with the extrusion of a lava flow, the VC-1 rhyolite, which is known only from the VC-1 corehole (Goff et al., 1986; Fig. 1).

After an indeterminate period, during which some erosion of the partly welded top of the Battleship Rock ignimbrite occurred, the third eruptive phase commenced with emplacement of a pyroclastic flow in the caldera moat. This was followed by effusive activity, production of the Banco Bonito lava, which occupies much of the southwestern moat area.

Petrology and Origin of the SW Moat Rhyolite Magma

The SW moat rhyolites display clear evidence of melt generation very shortly prior to eruption. All units are petrographically identical, apart from those differences imposed by eruptive style. Resorption and overgrowth textures predominate among crystals and crystal aggregates (Fig. 2), and mineral compositions are highly varied. The mineral assemblage is dominated by strongly resorbed grains of plagioclase (An_{16-51}) up to 3 mm in length, with lesser amounts of quartz, hornblende, biotite, hypersthene, augite, olivine, magnetite, ilmenite, and accessory apatite and zircon in high-silica rhyolite glass (76.0%–77.8% SiO_2). Quartz grains are invariably resorbed. Mafic minerals typically show complex overgrowth relations instead of resorption. Biotite is commonly overgrown by hornblende (Fig. 2A). Crystal aggregates (Fig. 2B) containing plagioclase, biotite, and pyroxene ± quartz, are also replaced by hornblende to varying degrees. The internal textures of these aggregates (Fig. 2B) are more suggestive of completely solidified igneous rock than of partly crystallized, glass-bearing cognate "cumulate" fragments of the type described by Tait (1988). We regard all of these inclusions, both single crystals and aggregates, as restitic. The resorption relations and the replacement of biotite by hornblende suggest strongly that much of the SW moat rhyolite magma was being heated up to the time of eruption.

Scarce small euhedral grains of plagioclase and hornblende, lacking reaction or resorption textures, are scattered through the high-silica rhyolite glass, and probably crystallized from the hot, high-silica melt. The compositions of the small plagioclase crystals (An_{41-54}) overlap with the most calcic zones in the large restite crystals. The small hornblende crystals have similar compositions to the hornblende overgrowths.

Banded mingled pumices are found throughout the SW moat rhyolites. The brown glass component in these is less silicic (72.5%–76% SiO_2) than the prevalent colorless glass. Associated with this brown glass is a crystal population characterized by Mg-rich pyroxenes (Mg# up to 78), titanomagnetite with up to 2.3 wt% Cr_2O_3, and olivine (Fo_{74}). We interpret these crystals and glass as representatives of a mafic magma, of probable basaltic andesite composition, that has mixed and largely hybridized with the rhyolitic magma.

The chief features of the petrology of the SW moat rhyolites, as outlined above, are predicted in almost every detail by the dynamic model of Huppert and Sparks (1988) for the generation of silicic magma by fusion of crustal rocks at the upper boundary of a

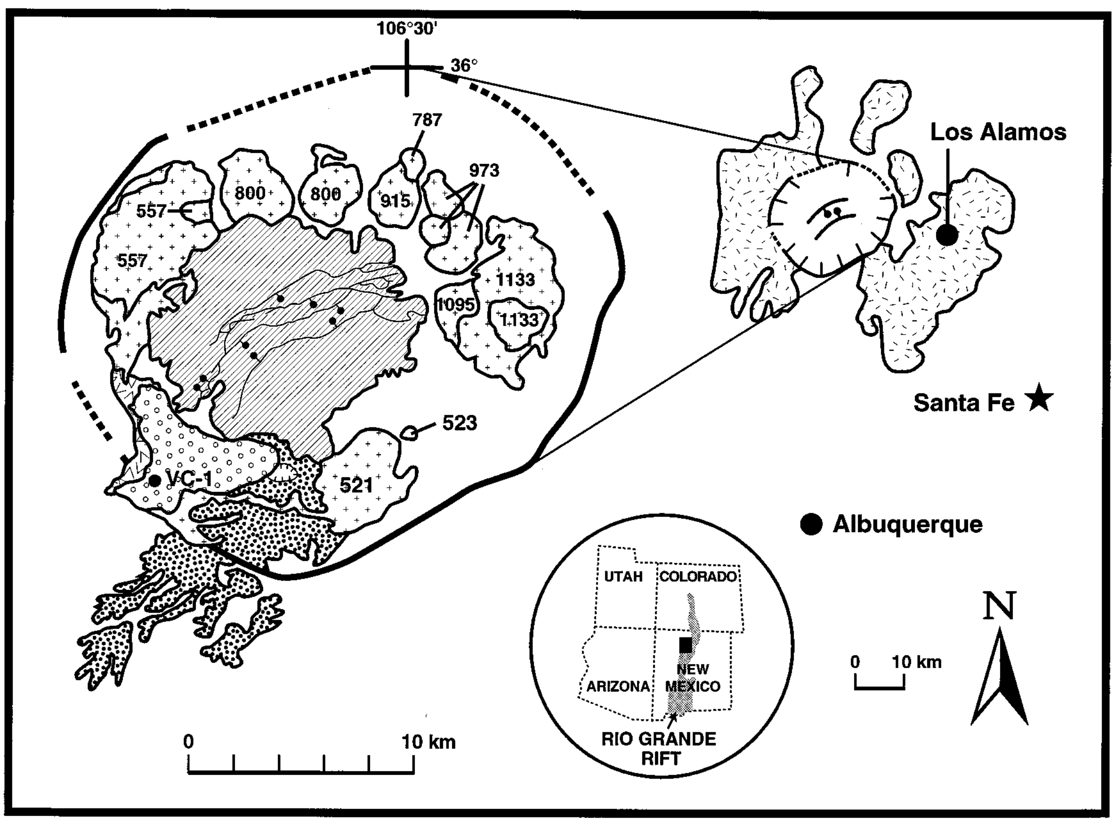

Figure 1. Maps showing location of Jemez Mountains volcanic field (JMVF) (solid square) at edge of Rio Grande rift in northern New Mexico (in circle) and location of JMVF and Valles caldera with respect to major population centers (upper right). Random dash pattern is present extent of Bandelier Tuff; details of caldera geology are on main map on left (after Smith et al., 1970). Heavy line is topographic rim of caldera; diagonal shading is resurgent dome; small crosses are postresurgent high-silica rhyolite lava domes and flows (Valle Grande Member of Valles Rhyolite); random pattern is Battleship Rock Member; heavy stipple is El Cajete Member; circle pattern is Banco Bonito Member. Numbers on Valle Grande domes are ages (in ka), from Spell and Harrison (1993). Note location of SW moat rhyolites vent area (hachured ovoid) and VC-1 CSDP core hole.

convecting mafic magma body emplaced into the crust. In this model, a proportion of the melting rock may survive in the anatectic liquid as restite, and is accompanied by crystallization of the same assemblage as heat is lost to the melting roof (Fig. 3). Eruption of the magma at this stage would preserve the restite textures, and cause some mingling with the subjacent mafic magma through drawdown effects. Thus, the SW moat rhyolite magma erupted while it was still being generated through melting of an intrusive—probably granodioritic—rock body by basaltic andesite magma emplaced into the subcaldera crust (Fig. 3).

Age of the SW Moat Rhyolites

The SW moat rhyolites rocks have proven extraordinarily difficult to date, due largely to the unequilibrated nature of the crystal assemblage. Published fission-track ages (Marvin and Dobson, 1979; Miyachi et al., 1985) have large errors and do not constrain the time of the SW moat rhyolite eruptions within the 0.52 m.y. since the latest Valle Grande high-silica rhyolite eruption of South Mountain. The SW moat rhyolites are essentially undateable by U-Th disequilibrium methods (Self et al., 1991). Spell and Harrison (1993) showed that SW moat rhyolite biotites contain excess Ar and for the most part give geologically unreasonable old ages, but they argued that the youngest apparent $^{40}Ar/^{39}Ar$ age of 205 ka provides an older age limit for the SW moat rhyolites.

Toyoda et al. (1995) obtained eruptive ages of 45 to 73 ka by electron spin resonance (ESR) dating of quartz grains from the El Cajete and Battleship Rock units of the SW moat rhyolites. Consistent with this are ^{14}C determinations on carbonized logs that indicate an age greater than 58 ka, and thermoluminescence (TL) dating of paleosols beneath the El Cajete fall deposits that constrain soil burial to <60 ka (S. L. Reneau, 1994, personal commun.).

The ESR results (Toyoda et al., 1995) constrain the age of the SW moat rhyolites to $\sim 60 \pm 15$ ka, and the ^{14}C and TL data suggest an age within a few thousand years of 60 ka. This young age of the SW moat rhyolites is very significant. These eruptions represent the first activity to have occurred for almost half a million years in the Valles caldera.

GEOPHYSICAL CONSIDERATIONS

If silicic melt were currently being generated beneath the Valles caldera, as happened with the SW moat rhyolites, high temperatures in the subcaldera crust may actually serve to mask seismic events that may be heralding impending volcanic eruptions. A number of studies have identified seismic anomalies, including low-velocity zones and/or attenuation of seismic waves, at shallow to mid-crustal depths beneath Valles caldera (Ankeny et al., 1986; Roberts et al., 1991, 1995; Lutter et al., 1995). A 5-km-thick low-velocity zone was identified recently beneath the caldera at

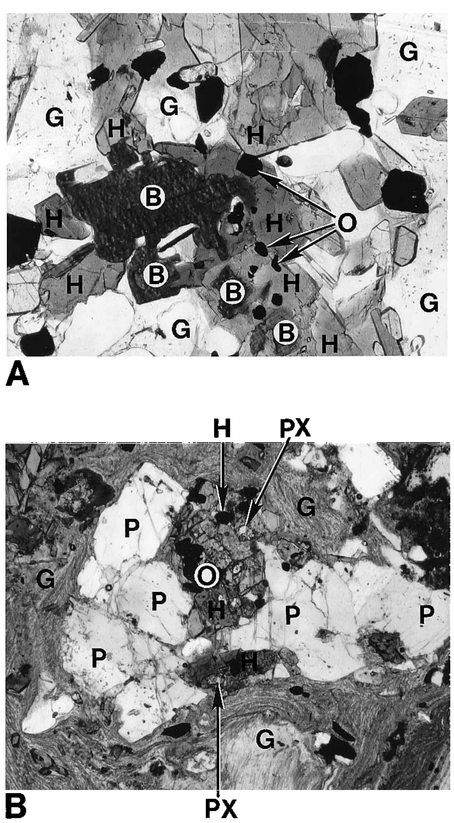

Figure 2. Photomicrographs of restite textures in SW moat rhyolites. P = plagioclase, H = hornblende, B = biotite, G = glass, O = opaque, and PX = pyroxene. A: Ragged biotite with hornblende jacket, Banco Bonito Member. Note optical continuity of biotite patches. Field width = 1.1 mm. B: Clot consisting of plagioclase, hornblende partly replacing biotite, and minor pyroxene and opaque minerals. Field width = 2.2 mm.

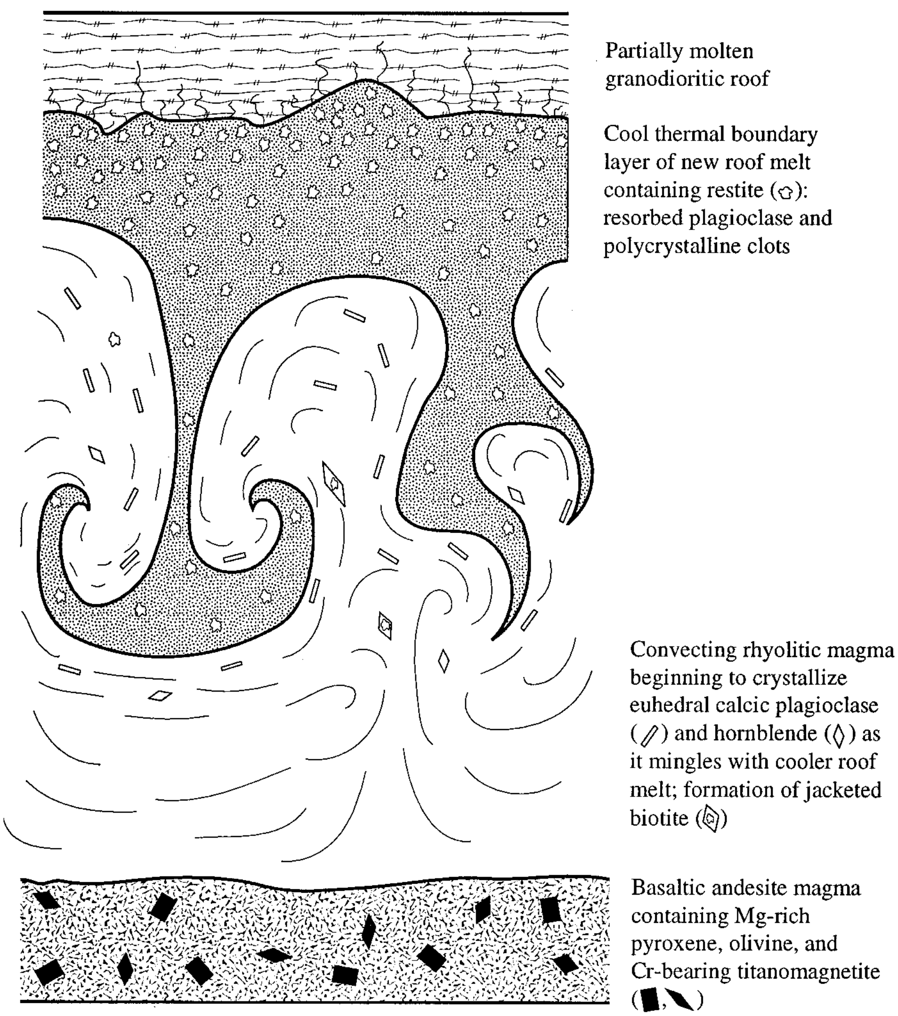

Figure 3. Diagram illustrating thermal and dynamic structure of SW moat rhyolite magma, at mid-crustal levels prior to eruption, after Figure 7 of Huppert and Sparks (1988); see text. Note mixing of relatively cool new melt containing restite with hotter rhyolite produced at earlier stage during melting event. Eruptive withdrawal further mixes liquids and their crystal populations, including subjacent mafic magma, which provides heat source.

depths around 30 km, presumably at the base of the crust (Lutter et al., 1995). The mid-crustal anomalies are attributed to high temperatures and possible pockets of residual melt associated with the cooling pluton that produced the Bandelier Tuff.

Also attributed to the effects of the large, cooling pluton is a notably aseismic zone coincident with the caldera, in contrast to abundant surrounding seismic activity (Cash and Wolff, 1984). The combined thermal effects of long-lived precaldera magmatism and the emplacement of mid-crustal plutons have resulted in elevation of the brittle-ductile transition to very shallow levels beneath the caldera. Thus, with such a thermal structure of the crust, deep intrusion of new magma batches, such as may be represented by the low-velocity zone 30 km beneath Valles caldera (Lutter et al., 1995), or possibly even mid-crustal intrusions, might have little or no seismic signature, and seismic monitoring will reveal intrusive, prevolcanic events only within a few kilometres of the surface.

DISCUSSION

There are a number of possible interpretations of the significance of the SW moat rhyolites in terms of their age, petrology, and place within the behavior pattern of the caldera since the second major Bandelier Tuff eruption at 1.22 Ma. One interpretation would place the SW moat rhyolite eruption as the terminal event of the postcaldera activity that formed the Valles Rhyolite over ~1 m.y. (e.g., Smith, 1979). The regularity and frequency of postcaldera eruptions between 1.22 and 0.52 Ma (Fig. 1), and the subsequent 0.46 m.y. dormancy, militate against this view, as does the different petrological character of the SW moat rhyolites (attributed to heating and melting of existing crust) from the earlier Valles Rhyolite units.

Another interpretation, which we favor, is that magmatism ceased between 521 and 60 ka, and that the SW moat rhyolites represent the onset of a new cycle of activity, ultimately due to renewed emplacement of mafic magma into the subcaldera crust. The scale of the mafic intrusive activity, which is unconstrained, will dictate the longevity of this cycle. Whereas the SW moat rhyolite eruption may represent an isolated magmatic event, it is equally possible that the lower crustal low-velocity zone detected by Lutter et al. (1995) may represent the present-day expression of renewed magmatism. If so, there is the possibility of a significant volcanic hazard to communities in and around the Jemez Mountains, including Los Alamos National Laboratory. Mullineaux (1976) identified the area as one with potential for future volcanism, including large explosive eruptions. On the basis of the past record, any future eruption would probably be, in part, explosive. We encourage establishment of a dedicated monitoring system, including seismographs, tilt meters, and periodic leveling surveys.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy Office of Basic Energy Sciences, the University of Texas at Arlington, the University of California, and Associated Western Universities, Inc. We thank the Baca Land and Cattle Co. and Copar Mining for allowing access to critical areas. Steve Self, Steve Reneau, Terry Spell, Fraser Goff, Tom Kolbe, John Carney, Mike Fehler, Leigh House, Peter Roberts, Lee Steck, and Scott Baldridge provided discussion and help. Constructive reviews of the manuscript were provided by Bob Christiansen, Steve Reneau, Terry Spell, D. M. Fountain, and an anonymous reviewer.

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Manuscript received September 30, 1994
Revised manuscript received January 25, 1995
Manuscript accepted February 6, 1995