Field characteristics of the El Cajete pumice deposit and associated southwestern moat rhyolites of the Valles Caldera

John A. Wolff, J. N. Gardner, and S. L. Reneau

1996, pp. 311-316. https://doi.org/10.56577/FFC-47.311

in:

Jemez Mountains Region, Goff, F.; Kues, B. S.; Rogers, M. A.; McFadden, L. S.; Gardner, J. N.; [eds.], New Mexico Geological Society 47th Annual Fall Field Conference Guidebook, 484 p. https://doi.org/10.56577/FFC-47

This page is intentionally left blank to maintain order of facing pages.

FIELD CHARACTERISTICS OF THE EL CAJETE PUMICE DEPOSIT AND ASSOCIATED SOUTHWESTERN MOAT RHYOLITES OF THE VALLES CALDERA

J. A. WOLFF[1], J. N. GARDNER[2] and S. L. RENEAU[2]
[1]Department of Geology, University of Texas at Arlington, Box 19049, Arlington, TX 76019;
[2]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract—Previous studies of the 50-60 ka southwestern moat rhyolites in the Valles caldera have underestimated the complexity of the eruption sequence they record. Based on new quarry exposures, and re-examination of roadcuts along NM-4, we recognize them as the products of a single eruption consisting of three cycles, each beginning with explosive activity and terminating with effusion of lava. The first cycle was dominated by plinian fallout, dispersed to the southeast of the vent which makes up part of the El Cajete pumice. A pyroclastic surge erupted during this cycle levelled a forest of tree trunks projecting from the initial fallout accumulation. This sequence ended with extrusion of a lava, progressively destroyed during explosive eruptions of the second cycle, during which activity gradually shifted from fallout-dominated to flow-dominated. The plinian falls are dispersed to the south, while the pyroclastic flows largely moved in a westerly direction along the caldera moat and into the head of San Diego Canyon to form the Battleship Rock ignimbrite. The last phase of this cycle produced a lava, found only in the VC-1 core. The third and last cycle began with eruption of an ignimbrite, but is mainly represented by the Banco Bonito lava, which dominates the modern topography of the southwestern Valles caldera moat.

INTRODUCTION

Southwestern moat rhyolites (SWMR) is used here as an informal term for the El Cajete, Battleship Rock and Banco Bonito members of the Valles Rhyolite of Bailey et al. (1969), the VC-1 rhyolite of Goff et al. (1986), and associated minor volcaniclastic beds. Together, these units constitute the youngest volcanic rocks associated with the Jemez Mountains volcanic field (Toyoda et al., 1995; Reneau et al., 1996). We contend that they represent a complex eruptive sequence of interspersed plinian, pyroclastic flow, and lava extrusion events that can be grouped into three cycles. Their young age (50–60 ka), their eruption after a very long hiatus in volcanic activity in the caldera (0.46 Ma), and their petrologic character are all consistent with the SWMR representing a new stage in the magmatic history of the caldera (Wolff and Gardner, 1995).

Here we describe our preliminary interpretation of the SWMR units, emphasizing the El Cajete pumice deposit, based on exposures in roadcuts along NM-4, and in the Copar pumice quarry approximately 2 km west of Las Conchas campground (Fig. 1). The observations summarized in this report should serve the reader as a guide to understanding SWMR exposures that are accessible to the public. Based on our findings to date (early 1996), we regard all SWMR units as products of a single lengthy eruption that went through three cycles of explosive activity followed by lava extrusion. We emphasize, however, that due to poor exposure, we do not yet precisely understand the stratigraphic relationship between the Battleship Rock ignimbrite, the upper part of the El Cajete, the VC-1 lava, and the opening explosive phase of the Banco Bonito eruption.

Petrologically the SWMR rocks form a coherent entity that is quite distinct from the rest of the Tewa Group (the caldera-related rhyolites, including the caldera-forming Bandelier Tuff, of Bailey et al., 1969; see Roadlog 2, this volume), which is dominated by quartz-sanidine high-silica rhyolites. All members of the SWMR are chemically and petrographically identical, except for differences imposed by eruptive style (e.g., vesicularity, fragmentation). They are characterized by phenocrysts of resorbed plagioclase and quartz, biotite reacting to hornblende, and a minor component of crystals derived from more mafic magma. Wolff and Gardner (1995) interpreted these textures as the result of melting of pre-existing igneous rock in the sub-caldera crust, followed by rapid rise and eruption of the new melt. The thermal input required for melting was

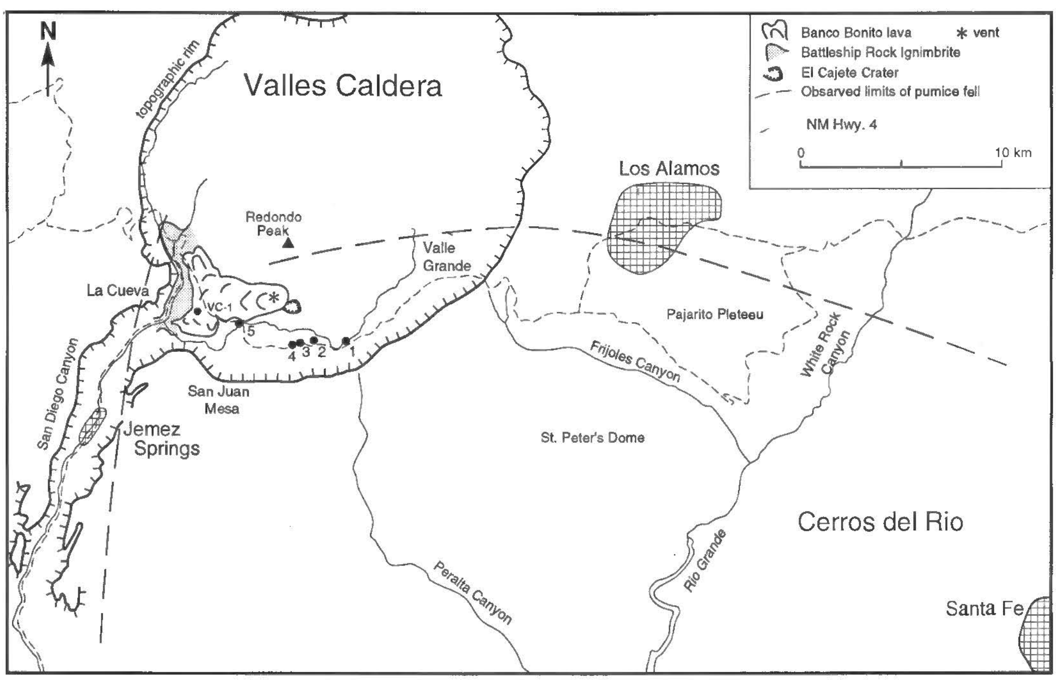

FIGURE 1. Location map showing sites referred to in the text and in Figure 2. The approximate outer limits of observed El Cajete fallout are shown by the broad dashed line. Numbered large black dots are 1, Las Conchas campground; 2, Copar Mine; 3, Roadcut 4.6; 4, Roadcut 4.7; 5, East Fork crossing (key section of Self et al., 1988).

supplied by intruding mafic magma. In the field, pale green haloes of clinopyroxene around resorbing quartz, common in hand samples of El Cajete pumice, are the most prominent evidence of crystal resorption. Compositionally banded black-and-white pumices, consisting of mingled rhyolitic and andesitic magmas, are occasionally found in the Battleship Rock ignimbrite.

PREVIOUS WORK

The principal units of the SWMR were defined by Bailey et al. (1969) as the Battleship Rock (lowermost), El Cajete, and Banco Bonito (uppermost) Members of the Valles Rhyolite Formation. At its type locality in San Diego Canyon, the Battleship Rock Member consists of welded ignimbrite with a distinctive densely welded interior containing prominent black vitrophyric fiamme. The El Cajete Member, named for El Cajete crater in the southern moat of the Valles caldera, is a pumice fallout deposit of plinian character, dispersed over a large area of the southern Jemez Mountains and the adjacent southern Española basin. The Banco Bonito Rhyolite vitrophyre flow, which dominates the topography of the southwestern caldera moat area, extends westward from El Cajete crater into the head of San Diego Canyon and toward the Sulphur Springs area.

The VC-1 CSDP corehole (Fig. 1) penetrated the SWMR in a paleotopographic low, and sampled an additional lava, the VC-1 rhyolite (Goff et al., 1986). Welded tuffs in VC-1, of general petrographic similarity to the SWMR, were designated as the VC-1 tuffs by Goff and Gardner (1987), and correlated to SWMR surface exposures at the head of San Diego Canyon by Self et al. (1988). Subsequent work (Self et al., 1991) reassigned the VC-1 tuffs to the Battleship Rock Member, but retained the VC-1 rhyolite as a separate unit, not represented in any surface exposure. Self et al. (1988, 1991) also reversed the Battleship Rock–El Cajete stratigraphy of Bailey et al. (1969), based on a tentative correlation of non-welded pyroclastic flow units within the upper part of the El Cajete sequence with the welded tuff at the Battleship Rock type locality.

The published work on these units could best be described as a history of conflicting interpretations. In part, this is due to the paleotopographic setting of available exposures, most of which are located at the steep edges of a major drainage, now represented by the East Fork of the Jemez River; correlations of pyroclastic units are consequently difficult. Our work broadly supports the conclusion of Self et al. (1991) that the SWMR represent an eruption sequence that was initially dominated by plinian fallout, followed by ignimbrite deposition, and terminated by extrusion of the Banco Bonito Rhyolite lava. However, the eruption cycles we see are more complex, and include two lava extrusion episodes not widely recognized.

Recently Wolff and Gardner (1995) and Reneau et al. (1996) emphasized that the 50–60 ka age and petrologic character of the SWMR, the geophysical evidence for magma beneath the Valles caldera, and the history of associated Quaternary hydrothermal activity indicate that the SWMR may represent the onset of a new stage in the history of Valles magmatism, with a possibility of higher long-term risk of future explosive volcanic eruptions in the caldera than previously recognized.

PALEOTOPOGRAPHIC SETTING

El Cajete crater is located at the head of a broad west-draining valley bounded on the north by Redondo Peak, on the east by South Mountain, and on the south by the Valles caldera wall. Within this valley an east-west ridge, roughly 60 m high on its southern side, separated the areas of El Cajete crater and Vallecitos de los Indios. This ridge is probably the topographic expression of a flow unit of South Mountain lava, which is continuously exposed along the East Fork of the Jemez River between Las Conchas campground and the East Fork crossing (Smith et al., 1970). The head region of the Banco Bonito lava is confined to the north of this ridge. The best exposures of the proximal El Cajete, along or near NM-4, are mostly south of the ridge; those in the sector from south to southeast of El Cajete crater are at the foot of the caldera wall. The only exception is the exposure just west of the East Fork crossing (the "key section" of Self et al., 1988), which is located on the northern side of the ridge.

The distribution of pyroclastic flow units was very strongly affected by the paleotopography. None surmount the caldera wall; El Cajete sections outside the caldera invariably consist only of fallout pumice. Fallout material also dominates most of the NM-4 exposures south of El Cajete crater; flow units are less than 2 m thick, and several thin to cm-scale fine ashes in short (<100 m) lateral distances. A single flow unit managed to partly climb the caldera wall west of Los Griegos, to an elevation of approximately 100 m above the caldera moat floor. We consider that the dominant mass of pyroclastic flow material (now buried by Banco Bonito lava) was discharged westward along the valley between Redondo Peak and the dividing ridge, and thence into San Diego Canyon. The VC-1 corehole is located almost on the axis of this paleovalley at the head of the pre-SWMR San Diego Canyon, which accounts for why it preserves a more complete section of topographically controlled units (pyroclastic flow deposits and lavas, see below) than does any single surface exposure. Essentially the same conclusion was reached by Self et al. (1988, 1991). The difficulties of establishing rigorous correlations between the El Cajete and Battleship Rock Members are largely due to the lack of overlap between the characteristic welded Battleship Rock and characteristic coarse pumice fallout of El Cajete.

DESCRIPTION OF UNITS

General

From the southern end of Valles Grande to the area of the East Fork crossing (Fig. 1), the SWMR are represented by pumice fallout units of the El Cajete interspersed with thin pyroclastic flow and surge deposits. Each of the latter vary from moderately well-sorted layered deposits with abundant sedimentary structures to massive, poorly sorted structureless beds with pumice clasts supported in a matrix of fine ash. Following common usage, we refer to those units dominantly composed of the former type as pyroclastic surge deposits, and the latter as pyroclastic flow deposits. Flow deposits frequently attenuate laterally to centimeter-thin fine ash beds. Flows and surges thin toward mountainous topographic highs, and none occur outside the Valles caldera. The pumice fallout, in contrast, is found across the southern Jemez Mountains, in the St. Peter's Dome area and on the Pajarito Plateau as far east as White Rock Canyon, with scattered patches on the Cerros del Rio volcanic field near Santa Fe.

Westward from the Copar mine toward the East Fork crossing (Fig. 1), the lower fallout units thin while the pyroclastic flow units become thicker as the elevation drops. One fallout unit (Unit F, see below) can be traced to the East Fork crossing and the key section of Self et al. (1988), where it forms the lowermost coarse fall unit (unit B of Self et al., 1988). Thus early El Cajete fallout deposits (A B and D, see below) are not represented at the key section of Self et al. (1988).

The pyroclastic flow units interbedded with fallout in the upper part of the El Cajete (Fig. 2) are interpreted as equivalent to Battleship Rock ignimbrite. In exposures within a few kilometers of the vent, the units are texturally variable from poorly sorted and massive, with pumices up to 70 cm, to moderately sorted and fines-poor with sedimentary structures. Farther west, around La Cueva, the flow units are thick, poorly sorted, "classic" valley-fill ignimbrite. At the Battleship Rock type locality (Bailey et al., 1969), the ignimbrite consists of two cooling units (Self et al., 1991), the lower of which has a densely welded interior portion.

The succeeding unit is a vitrophyric lava known only from the VC-1 corehole (the VC-1 rhyolite). This unit marks the end of the second SWMR eruptive cycle and in the VC-1 core is overlain by silt. This pause in eruptive activity is represented by an erosion horizon at the top of the Battleship Rock ignimbrite in upper San Diego Canyon.

Activity resumed with the eruption of a coarse, very lithic-rich ignimbrite containing abundant blocks of glassy, densely welded Battleship Rock tuff. This unit was described as "proximal Battleship Rock ignimbrite" by Self et al. (1988), and known only from one surface exposure (Location B, fig. 8 of Self et al., 1988) and the VC-1 core. Because we consider this unit to be the product of the same eruption phase as the Banco Bonito lava, we refer to it here as the Banco Bonito ignimbrite.

The final product of the SWMR eruptions is the Banco Bonito lava, which is largely intact. It consists of a pumiceous to vitrophyric carapace with a stony rhyolite interior.

Detailed descriptions of individual El Cajete units follow (Fig. 2). We have divided the SWMR sequence into three parts, based on overall stratig-

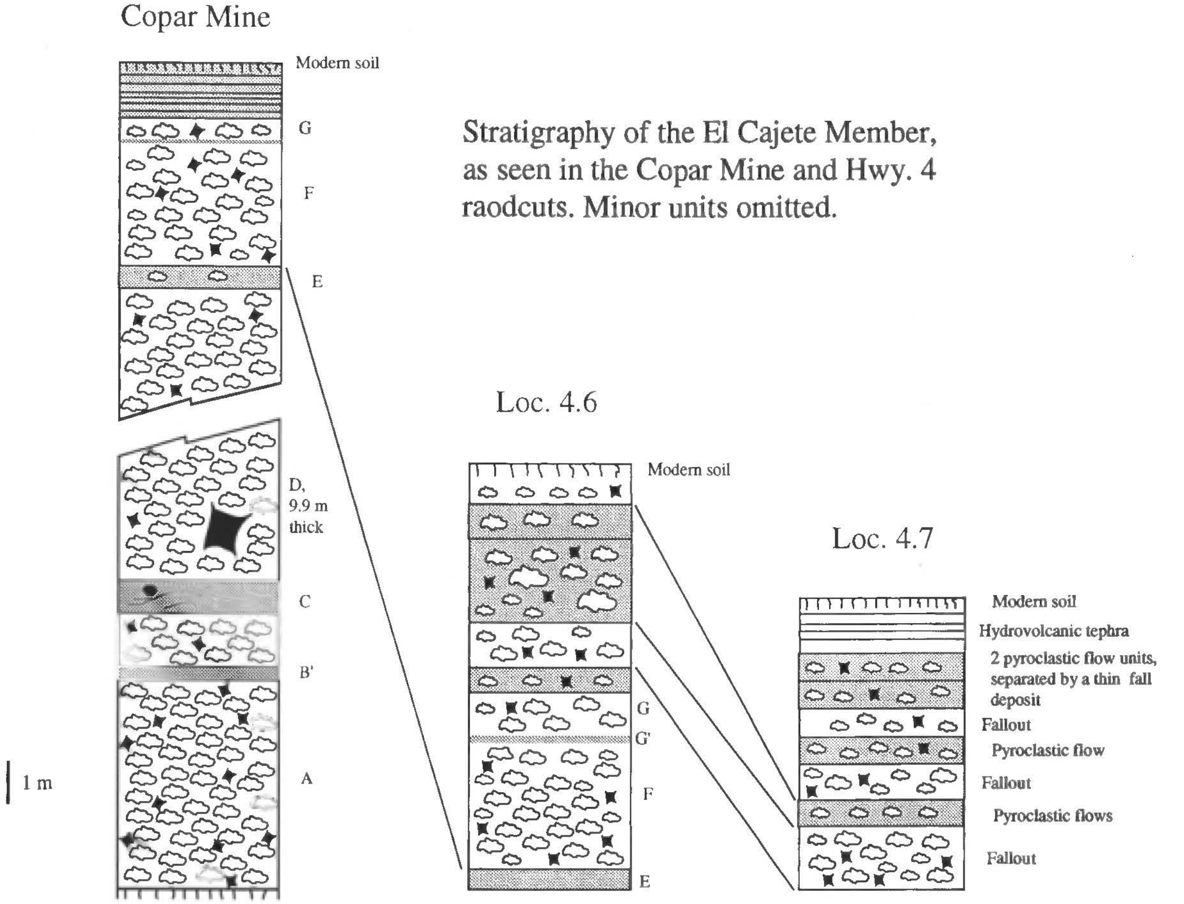

FIGURE 2. Correlated measured sections through the El Cajete Member; see Figure 1 for locations. Pyroclastic flow deposits above unit G are thought to correlate with the Battleship Rock ignimbrite (see text).

raphy, and the dense fragment content of pyroclastic units. This scheme differs from previous usage.

First eruptive cycle—the lower El Cajete Member

In the area of the Copar mine and southern Valle Grande, fall unit A sits on a substrate that varies from clay-rich soil to bare rock. On the soil is a thin (few mm) black organic layer, and unit A contains occasional empty vertical tree molds 10–40 cm in diameter. Unit A, with a maximum observed thickness of 5.5 m in the Copar mine, consists of coarse pumice fallout of plinian type, with a low content of lithic fragments of densely welded Bandelier Tuff, Keres Group andesites and dacites, and rare fragments of friable sandstone. The lithics vary from fresh (rare) to intensely hydrothermally altered. Subtle variations in pumice size and sorting through A suggest a fluctuating column and/or changing wind velocity during emplacement. There is no lithic-rich layer at the base that could be ascribed to initial vent-clearing activity, despite the proximity to the vent (2–3 km).

Unit A is overlain by a thin pyroclastic flow B′, which has a maximum observed thickness of 35 cm at Loc. 4-5 (Fig. 1). In the Copar mine, B′ consists of a fine ash layer (Fig. 3) with characteristics that indicate deposition from a flow, rather than an atmospherically-supported co-ignimbrite ash cloud. B′ is absent in a roadcut only 300 m away from the Copar mine. B′ and the layer of coarse pumice immediately beneath are usually iron-stained, probably due to perching of water at the permeability contrast.

Fall unit B consists of reversely graded coarse pumice fallout, very similar to fall unit A, with a maximum observed thickness of 135 cm (Figs. 2, 3). The basal 4 cm are strongly reversely graded in pumice and lithic size, which suggests that deposition of flow B′ was due to a temporary failure of the buoyant plinian column rather than simultaneous fall-and-flow eruption; the same relationship is repeated at the bases of fall units D, F and G, higher in the sequence. Like Unit A, B is also penetrated by vertical tree-trunk molds.

Unit C is a moderately well-sorted, bedded surge deposit 15–120 cm thick with sedimentary structures and abundant subhorizontal tree molds 4–32 cm in diameter. The tree molds often contain charcoal which has been dated at 50.1 ± 1.3 to >58 ka (Reneau et al., 1996). The preservation of charcoal in unit C, and its absence from vertical tree molds in underlying fall deposits, suggests that C was hot enough to burn trees, whereas the fallout pumice was not; after the eruption, the charcoal was preserved but the wood in vertical tree casts rotted away. This further implies that flow C had sufficient power to snap off trees with trunks up to 32 cm in diameter; many molds penetrate a short distance (10s of cm) into the overlying fall unit, D, suggesting a tendency for trees to be sheared off slightly above the surface of B, probably due to a velocity gradient at the base of the C surge cloud. Detailed mapping of tree mold orientations in the Copar mine suggests that either the vent for surge C was located in the western part of the El Cajete crater, or that there was a slight change in flow direction (Fig. 4). C shows systematic textural differences with the slope of the surface on which it is deposited. Although the topography on top of fall unit B in the Copar mine is fairly gentle, C is consistently coarser and thicker on vent-facing slopes than on flat ground and lee slopes (Fig. 5). This is consistent with sedimentation of the deposit from an expanded cloud thicker than the local relief; the effect is identical to that of a snowstorm in a strong wind, where snow piles up against windward slopes. C forms the base of the SWMR sequence in the Vallecitos de los Indios area, consistent with a southeast–east dispersal for the accompanying fallout units.

Fall unit D, 9.9 m thick in the Copar mine, was the product of the most powerful phase of the first eruptive cycle. Occasional 1-m diameter lithic clasts were unearthed during quarrying operations (the maximum diameter observed in situ was 70 cm), although pumices are rarely larger than 30 cm. However, the faint discontinuous lensoid bedding, and the high abundance (>50%) of pumice clasts with fracture surfaces and sharp edges, as opposed to ragged "torn liquid" morphologies, suggest that the

FIGURE 3. The El Cajete deposit in the Copar Mine. A, lower units draped over paleotopography; units shown are, from bottom to top, fallout unit A, thin dark ash layer of unit B′, fallout unit B, surge unit C, and fallout unit D. B, vertical tree mold in fallout unit B and horizontal tree mold in surge unit C. C, lithic bomb impact structure in fallout unit B, with a zone of smashed pumice and deformed layers beneath the bomb. D, from the bottom fallout unit D, surge unit E (dark layer), and fallout unit F. Above F is a complex series of pyroclastic flow/surge units with interbedded fallout deposits. Section is capped with soil.

D pumice fell as very much larger clasts—perhaps up to a few meters in diameter—which shattered upon impact (like the Askja plinian fallout deposit, Sparks et al., 1981).

Further evidence of the fragility of pumice in fallout units A, B and D is provided by pockets of smashed pumice beneath lithic bombs. These features are impact structures, analogous to bomb sags found in fine-grained ash deposits. They are most abundant in the Copar mine (Fig. 3) and nearby roadcuts. The long axes of some pockets are vertical, but many are elongated in a downward diagonal direction away from vent, and record oblique bomb trajectories. At the Copar mine, units A and B contain a far higher proportion (90%) of angled impact structures than does unit D (40%), suggesting a possible change in the height and/or angle of the gas-thrust portion of the eruption column (Wilson, 1976) between eruption of B and D.

El Cajete pumice is abundant outside the caldera over the central and southern part of the Pajarito Plateau (Self et al., 1988, 1991) and the southeastern Jemez Mountains, including the St. Peter's Dome area (Goff et al., 1990). Along NM–4 on Frijoles Mesa, south of Los Alamos, 2.2 m of fallout occurs at 24 km from the vent. Based on lithic assemblage, the St. Peter's Dome–Pajarito Plateau fallout is correlated with units A, B and D. Because flow/surge units B′ and C have not been found outside the caldera, the individual fall units cannot be distinguished.

The first eruptive cycle ended with the intrusion of magma into a shallow portion of the vent, and, probably extrusion of a lava dome in the crater. The existence of this dome is inferred from abundant rhyolitic vitrophyre clasts among the lithic assemblage of succeeding units.

Second eruptive cycle—
the upper El Cajete and Battleship Rock Members

Fall D is overlain by a distinctive pink-tinged thin pyroclastic flow, E. The pink coloration is derived from small fragments of an intensely red, hydrothermally altered rock. E varies from 0 to 65 cm thick, and typically has a higher proportion of fine clasts than C. It forms the base of the El Cajete sequence in exposures near the East Fork crossing.

The most notable feature of E and all higher units is the presence of abundant dense vitrophyre clasts, which are the defining characteristic of the upper El Cajete. The assemblage, abundance, and textural relations of phenocrysts in this vitrophyre are identical to those of the rest of the SWMR, and the vitrophyre clasts are therefore cognate. Groundmass textures vary from featureless dense glassy to flow-banded, with the banding due to differences in vesicularity; some clasts have fiamme-like structures. Occasional lithic fragments are enclosed in the glass. Many clasts are perlitized and somewhat friable. This range in textures is characteristic of silicic lavas. The abrupt appearance of the vitrophyre fragments in the sequence can be explained by a short hiatus in explosive activity during which a lava dome grew in the vent. The renewal of violent eruptions, with flow E, eroded and eventually destroyed this dome. No sign of erosion of the top of fall unit D has been observed, therefore the hiatus was of short duration.

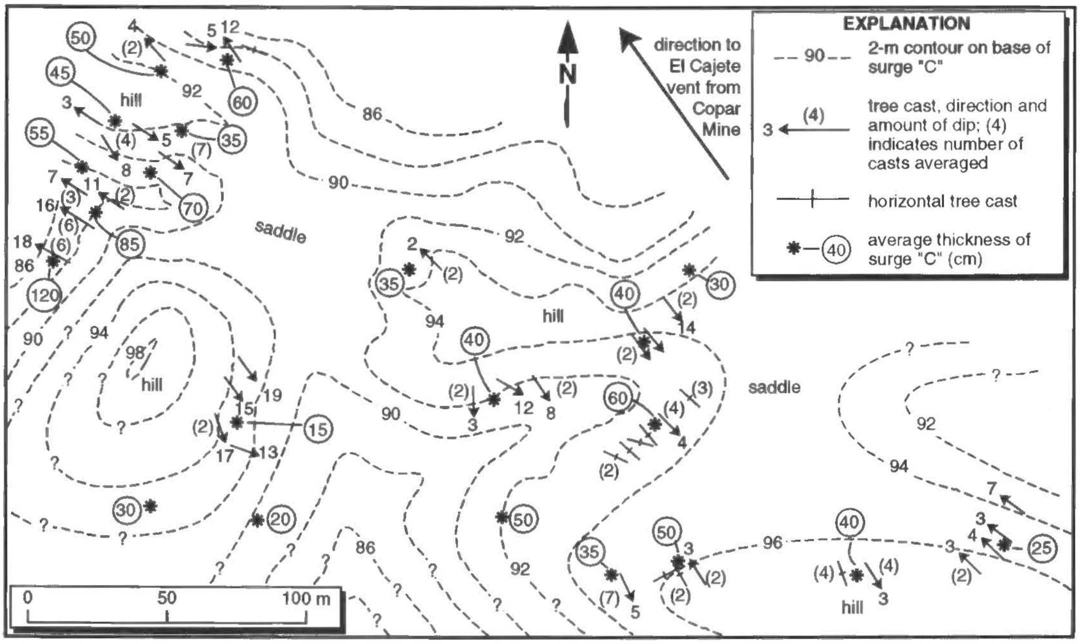

FIGURE 4. Paleotopographic map of the base of surge C of the El Cajete pumice at the Copar Mine, showing orientations and dips of 100 subhorizontal tree molds within the surge bed and spatial variations in the average thickness of the surge bed. Paleotopography based on about 275 surveyed points on surge C and underlying and overlying stratigraphic markers; surveying performed between April 1992 and June 1994 with theodolite or total station, revisiting the quarry as it expanded. Surge thicknesses based on 169 measurements, grouped into similar paleotopographic settings. Topography uses arbitrary datum.

Overlying fall unit F marks a resumption of plinian deposition. It is the only unit that is easily recognizable over the whole area of exposure from the Copar mine to the East Fork crossing. It consists of coarse plinian fallout with abundant vitrophyre lithics. It is dispersed south-southwest of the El Cajete vent, and makes up most of the thickness of the deposit in the area of Vallecitos de los Indios. It drapes the adjacent caldera wall and rests directly on welded Bandelier Tuff on San Juan Mesa. Due south of El Cajete crater, the top of F is marked by a thin fine ash bed, G′, which thickens westward into an ignimbrite consisting of one to three flow units. It is overlain by fall unit G, texturally indistinguishable from F, and reversely graded in the basal few centimeter. Above G, the El Cajete consists of a complex series of at least seven pyroclastic flow/surge packages, some having multiple flow units, and interbedded fall deposits. The falls are generally finer grained and have a higher lithic content than F and G, with abundant fragments of brown, densely welded Bandelier Tuff in addition to vitrophyre and other lithics derived from the Keres Group. The flows are lateral correlatives of the Battleship Rock tuff, the main mass of which was emplaced further west at lower elevation. The complete sequence is exposed in roadcuts due south of El Cajete crater.

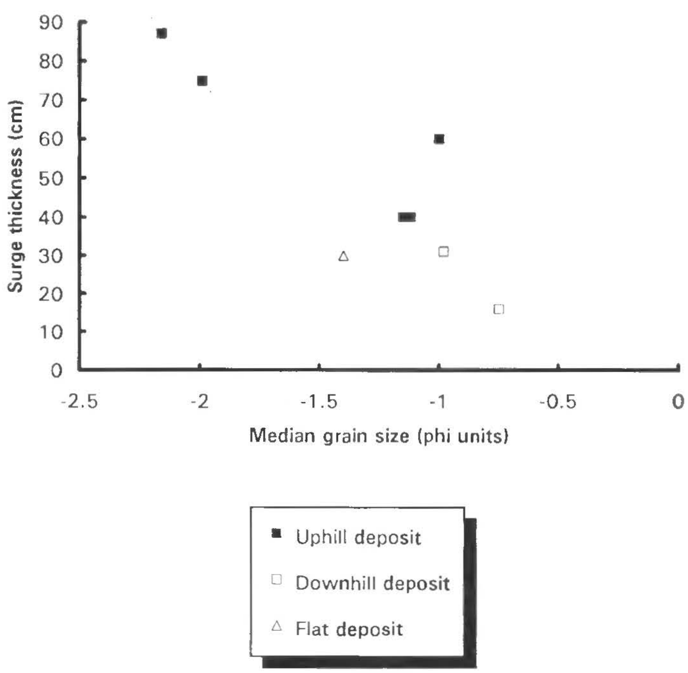

FIGURE 5. Variation in grain size (from sieve data) and thickness of pyroclastic surge C as a function of paleotopography. "Uphill deposit" refers to vent-facing slopes; "downhill deposit" to slopes facing away from the vent, and "flat deposit" to approximately horizontal paleotopography.

The uppermost unit exposed in this area consists of stratified, variably sorted fallout material dominated by coarse sand-sized, poorly vesiculated glassy fragments. It is interpreted as the product of hydrovolcanic explosions at or near the end of the second eruptive cycle, which concluded with the extrusion of the VC-1 lava, not exposed at the surface. The precise stratigraphic relation of the hydrovolcanic tephra and the VC-1 lava, however, remains unclear; the hydrovolcanic tephra does not appear in the VC-1 core.

The post-G stratigraphy has not been rigorously extended away from the roadcuts mentioned above. Outside the caldera, F and G are exposed on the west side of Cerro Pelado 6 km south of the El Cajete vent. The El Cajete crater ring consists mostly of upper El Cajete falls and flows/surges, although a vitrophyre-free fallout unit, presumably D, is exposed at the topographic base of the structure on the southeast side. Finally, on the basis of lithic assemblages and paleotopography, the nonwelded to partly welded ignimbrites exposed west of the Banco Bonito lava, mapped as Battleship Rock by Smith et al. (1970), are correlated with the post-G flows of the upper El Cajete. However, the lack of intervening exposures and the dispersal of the fallout units away from this area makes specific identification of flow units difficult.

The details of our different interpretation of El Cajete stratigraphy from that of Self et al. (1988) mostly concern the relation between what we regard as the first and second eruptive cycles, and should perhaps be clarified with respect to the roadcut exposures just west of the East Fork crossing, which make up the "key section" of Self et al. (1988). In our scheme, there are no primary deposits of the first eruptive cycle at that location. All of the pyroclastic fallout and flow units have abundant vitrophyre clasts, and thus, by our definition, are products of the second cycle. The lowest coarse plinian fall deposit correlates with our unit F, and two fallouts higher in the section (D and F of Self et al., 1988) probably are equivalent to our unit G; they are separated by a thin ignimbrite that is not seen elsewhere and does not have a correlative thin ash on the local small paleotopographic high. Due to erosion, the overlying rich stratigraphy of the upper El Cajete (Fig. 2) is almost unrepresented. Also, we regard the upper clastic units (J and K of Self et al., 1988) at this section as younger, post-volcanic fluvial deposits related to the downcutting of the East Fork of the Jemez River, and the overlying boulder bed as Banco Bonito-derived canyon-wall colluvium, of relatively recent origin.

Third eruptive cycle—the Banco Bonito ignimbrite and lava

A significant pause in activity occurred after the hydrovolcanic activity that closed the second cycle. This pause is marked by local erosion of the upper El Cajete and Battleship Rock (Self et al., 1988) and the deposition of minor sediments. The third cycle began with eruption of an ignimbrite, known from the VC-1 core and a single surface exposure (the "proximal Battleship Rock" of Self et al., 1988; see their fig. 14), which contains abundant lithic fragments of welded Battleship Rock ignimbrite. No plinian deposits that could be assigned to this third cycle have been found. The main product, and the youngest volcanic unit of the entire Jemez Mountains volcanic field, is the Banco Bonito lava. At most exposures, the lava is a massive black vitrophyre, frequently flow-banded, with occasional xenoliths. More detailed descriptions were given by Bailey et al. (1969) and Self et al. (1988). Much of the original surface relief is preserved; ogives are apparent on aerial photographs. Low spots on the lava surface are today filled with a fine gray silt, probably loess.

ACKNOWLEDGMENTS

This work was supported through the Los Alamos National Laboratory Seismic Hazards Investigation Program, and by Associated Western Universities and the University of California through a faculty fellowship to JAW. We thank the Baca Land and Cattle Co. and Copar Mining for allowing access to critical areas, and John Carney, Marty Horn, Nathan Becker, and Alison Burchell for assistance in the field. We thank Fraser Goff and Terry Spell for helpful reviews.

REFERENCES

Bailey, R. A., Smith, R. L. and Ross, C.S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey, Bulletin 1274-P, p. 1–19.

Goff, F. and Gardner, J.N., 1987, Jemez volcanics cored in second D.O.E. hole: Geotimes, v. 32, p. 11–12.

Goff, G., Gardner, J. N. and Valentine, G., 1990, Geology of St. Peter's Dome area, Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 69.

Goff, F., Rowley, J., Gardner, J. N., Hawkins, W., Goff, S., Charles, R., Wachs, D., Maassen, L. and Heiken, G., 1986, Initial results from VC-1, first Continental Scientific Drilling Program core hole in Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1742–1752.

Reneau, S. L., Gardner, J. N. and Forman, S. L., 1996, New evidence for the age of the youngest eruptions in the Valles caldera, New Mexico: Geology, v. 24, p. 7–10.

Self, S., Kircher, D. E. and Wolff, J. A., 1988, The El Cajete series, Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, p. 6113–6127.

Self, S., Wolff, J. A., Spell, T. L., Skuba, C. E. and Morrisey, M. M., 1991, Revisions to the stratigraphy and volcanology of the post-0.45 Ma units and the volcanic section of VC-1 corehole, Valles caldera, New Mexico: Journal of Geophysical Research, v. 96, p. 4107–4116.

Smith, R. L., Bailey, R. A. and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Investigations Map, I-571, scale 1:125,000.

Sparks, R. S. J., Wilson, L. and Sigurdsson, H., 1981, The pyroclastic deposits of the 1875 eruption of Askja, Iceland: Philosophical Transactions of the Royal Society of London, v. A299, p. 241–273.

Toyoda, S. and Goff, F., 1996, Quartz in post-caldera rhyolites of Valles caldera, New Mexico: ESR fingerprinting and discussion of ESR ages: New Mexico Geological Society, Guidebook 47.

Toyoda, S., Goff, F., Ikeda, S. and Ikeya, M., 1995, ESR dating of quartz phenocrysts in the El Cajete and Battleship Rock members of the Valles Rhyolite, Valles caldera, New Mexico: Journal of Volcanology and Geothermal Research, v. 67, p. 29–40.

Wilson, L., 1976, Explosive volcanic eruptions—III. Plinian eruption columns: Geophysical Journal of the Royal Astronomical Society, 30, p. 381–392.

Wolff, J. A. and Gardner, J. N., 1995, Is the Valles Caldera entering a new cycle of activity?: Geology, v. 23, p. 411–414.