PHYSICAL VOLCANOLOGY OF SILICIC LAVA DOMES AS EXEMPLIFIED BY THE TAYLOR CREEK RHYOLITE, CATRON AND SIERRA COUNTIES, NEW MEXICO

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ABSTRACT

The Taylor Creek Rhyolite consists of lava domes and flows that are part of the middle Tertiary Mogollon-Datil volcanic field in southwestern New Mexico. This rhyolite was emplaced during at least 20 eruptions from as many vents distributed throughout an area of several hundred square kilometers. Each eruption appears to have gone through a unidirectional sequence, beginning with the formation of pyroclastic deposits and ending with the relatively quiet effusion of magma to form a lava dome or flow. Pyroclastic and lava deposits are about equally voluminous, and together they account for about 100 km^3 of erupted magma. The volume of individual domes ranges from somewhat less than 1 km^3 to about 10 km^3.

High-precision $^{40}Ar/^{39}Ar$ ages on sanidine phenocrysts, supplemented by the reconstructed length of the path of magnetic secular variation recorded in the lava domes and flows, suggest that the entire Taylor Creek Rhyolite lava field grew in a few thousand years or less. All eruptions tapped the same large reservoir of magma, and each eruption apparently was a continuous event so brief that a liquid viscous core existed throughout the growth of a typical dome or flow. The domes and flows are excellent examples of endogenous bodies, that is, bodies that grew from within.

During growth of the domes and flows, a flow-generated envelope of breccia formed around a flow-foliated coherent lava core. The breccia consists of blocks of flow-foliated lava tumbled to diverse orientations. Deposits of breccia are structureless, except locally at the lateral margins of a dome or flow where multiple gravity-driven debris avalanches accumulated in crudely layered sequences dipping outward at the angle of repose.

Within the coherent core of a dome or flow, flow foliation tends to be subhorizontal near the base and to fan steeply upward toward the top, apparently in response to upward-decreasing load on a viscous body spreading principally under the influence of gravity. A buttressing effect from flow breccia that accumulates at the lateral margins of a growing dome or flow enhances the tendency for steep upward fanning to develop. Subsequent stream erosion into a dome can be contained by steeply dipping foliation, thus favoring vertical downcutting at the expense of a lateral component.

The domes and flows occur in spatially separated clusters, within which relative ages of eruptive units generally can be determined from field relations, but between clusters relative ages are unknown. Vent locations within each cluster chart a variably east or west migration of activity, but migration always has a net northward component. Consideration of the brief duration of lava-field formation and a calculated mean of about 500 yr for a typical eruptive unit to cool to nearly ambient temperature indicates that some eruptions were simultaneous. The maximum number of eruptive units in a cluster is five, equivalent to about 2,000 yr if each intereruption period within this cluster was the mean cooling time to near ambient temperature. Two thousand years is indistinguishable from the life span of the lava field as suggested by magnetic secular variation recorded in the domes and flows.

Structural comparisons of Taylor Creek (and other) Rhyolite domes and flows with dacitic counterparts suggest that rhyolitic bodies tend to form through endogenous growth whereas dacitic bodies generally are of mixed endogenous and exogenous origins. This apparent difference may reflect characteristic contrasts in size and depth between rhyolitic and dacitic magma systems, and in the fluidity of the two magma types.

Various theoretical models that attempt to describe the formation of silicic domes and flows may be appropriate for individual growth events for the bodies of mixed structural origins, but the models cannot accurately portray a dome that forms from multiple effusive events that occur over years to decades. The dacite lava domes of historic age at Mount St. Helens, Washington, and Santiaguito, Guatemala, are examples of this type.

Taylor Creek Rhyolite and structurally similar domes of endogenous origin perhaps are most amenable to theoretical analysis, because each apparently had a liquid core that buffered a dome or flow toward endogenous growth throughout its formation. However, time-related changes in fluid- and solid-material properties that occur during lava-dome growth can complicate accurate theoretical portrayal of even these structurally simple bodies.

INTRODUCTION

The manner in which a silicic lava dome or flow grows reflects the interplay among such variables as magma fluidity at eruption (a function of composition, temperature, crystal content, volatile content, and so forth), and during subsequent emplacement on the ground surface, vent geometry, volumetric rate of eruption, size and depth of source magma reservoir, character of the shallow ground-water environment through which magma passes, and the shape of the landscape upon which lava emplacement occurs. The manner and rate of subsequent dome or flow erosion reflect interplay among the degree of consolidation of the outermost zone (often consisting of flow breccia), the degree of coherence of the nonbrecciated parts of the body, the spacing and orientation of flow foliation, effects of possible tectonic disruption, and climate.

Study of the physical features of the Taylor Creek Rhyolite domes and flows of New Mexico (fig. 1) provides a basis for evaluating the above-listed factors as they pertain to the growth and erosion for these silicic lavas and for making comparisons with analogous features in other silicic domes and flows. For convenience, we often refer to all of the Taylor Creek Rhyolite lavas as domes, even though formation of a few included a dominant component of lateral emplacement and thus implies "flow" as a more accurate descriptor.

No single dome of the Taylor Creek Rhyolite is exposed from base to pre-erosion top, but a complete cross-sectional representation of a dome can be constructed from information collected at outcrops of various structural levels exposed throughout the lava field. This cross-sectional structure suggests that the growth of a dome was a geologically continuous and brief event. A typical eruption apparently began with a pyroclastic phase that was immediately followed by the relatively quiet effusion of magma to form a foliated dome, which became enveloped with its own breccia during growth.

Erosion has removed most of this breccia from presently exposed levels of all Taylor Creek Rhyolite domes. However, remnants of the breccia along lateral margins are abundant enough to guide reasonably accurate reconstruction of the pre-erosional plan-view shapes of most domes. Erosion also has exposed parts of the base of one dome (unit Tt_{20}), and these exposures permit comparisons between breccia slowly cooled beneath the load of overlying lava versus breccia quickly cooled under virtually no load. Erosion also has carved steep-sided stream valleys along and near the contact between a few pairs of overlapping domes and in so doing illustrates how foliation can affect the course of a stream as it cuts downward into a dome. In addition, mapped stratigraphic relations in conjunction with the interpretation of physical features that help define vent location permit reconstruction of paths of vent migration in time and space. All of these physical aspects contribute to a reasonably complete understanding of how the Taylor Creek Rhyolite dome field grew and how it has been eroded.

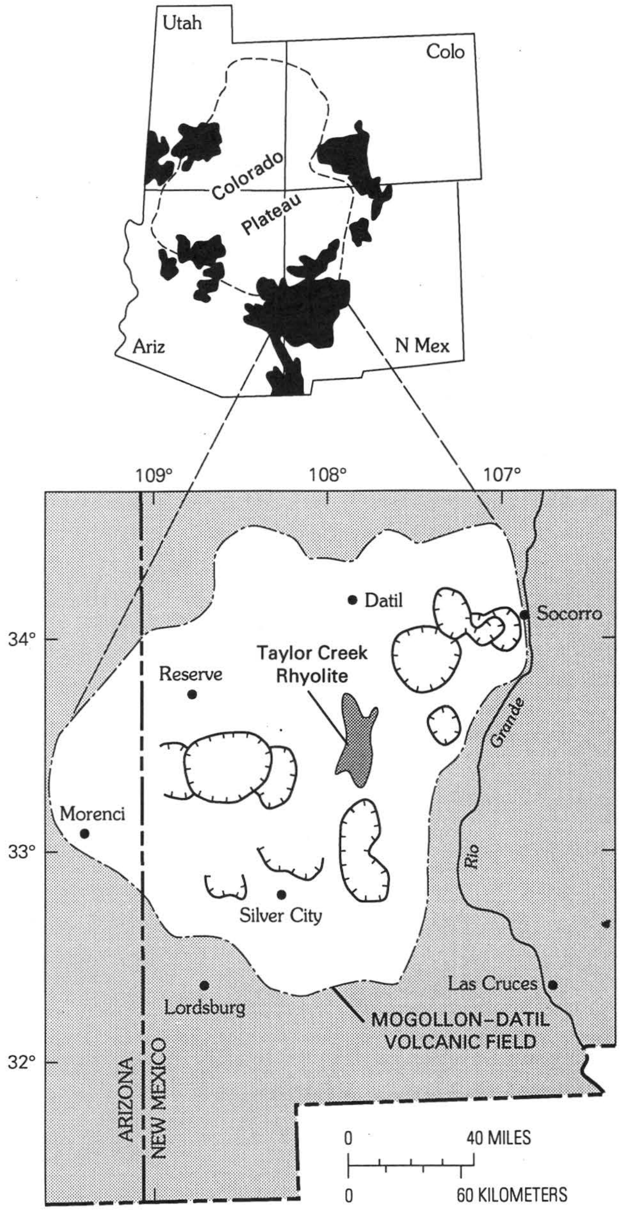

Figure 1. Cenozoic volcanic areas (black) around the Colorado Plateau, with enlarged view of Mogollon-Datil volcanic field. Hachured lines mark calderas.

ACKNOWLEDGMENTS

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GEOLOGY, GEOCHEMISTRY, AND GEOCHRONOLOGY

The Taylor Creek Rhyolite is within the east-central part of the middle Tertiary Mogollon-Datil volcanic field in southwestern New Mexico (fig. 1). Though nearly surrounded by middle Tertiary calderas (McIntosh and others, 1986, 1990; Ratte and others, 1984), some older and some younger than the rhyolite itself, and though sandwiched within the sequence of ignimbrites emplaced from vents marked by these calderas, the Taylor Creek Rhyolite apparently is not related to a caldera-forming cycle of volcanism. A magma reservoir that fed eruptions of Taylor Creek Rhyolite is interpreted to have been of caldera-forming size, but the magma may have been too poor in volatiles to produce a pyroclastic eruption voluminous enough to result in caldera collapse (Duffield and du Bray, 1990; Duffield and Dalrymple, 1990), or the magma may have lost considerable volatiles during ascent from the reservoir to sites of eruption (Webster and Duffield, 1991; Duffield and Ruiz, 1992a), or both. Instead, multiple leaks from the reservoir of magma resulted in the formation of a field of porphyritic lava domes.

The Taylor Creek Rhyolite contains about 15 to 35 volume percent phenocrysts, almost all of which are sanidine and quartz in subequal amounts. Other minor but ubiquitous phenocryst phases are oligoclase and hornblende. The mafic phenocrysts commonly are altered beyond unequivocal identification. Phenocrysts range in size from about 2 to 7 mm, and mean phenocryst size correlates with total volumetric phenocryst abundance (Duffield and Ruiz, 1992a,b). Nearly all of the groundmass of Taylor Creek Rhyolite devitrified while cooling. Vitrophyre was found at about 10 localities during field mapping.

Taylor Creek Rhyolite is of a nearly constant major-element composition that varies slightly across the boundary between metaluminous and peraluminous chemical types (Duffield and Dalrymple, 1990). Silica averages about 77.5±0.4 weight percent. Each species of feldspar phenocryst also is of nearly constant composition (Duffield and du Bray, 1990). Fluorine concentration in whole-rock vitrophyre is about 0.3 weight percent, which is high relative to that of average rhyolite. This high fluorine is partly expressed as topaz crystals that grew in lithophysae of some eruptive units from vapor emitted during cooling, degassing, and devitrification. Thus, Taylor Creek Rhyolite is classified as high-silica, topaz rhyolite (Christiansen and others, 1986). It also is sometimes referred to as tin rhyolite, as it is locally automineralized with cassiterite-bearing veinlets (Duffield and others, 1990).

Trace-element concentrations and $^{87}Sr/^{86}Sr_i$ in whole-rock samples vary considerably (Duffield and Ruiz, 1992a). Elements that are considered to be relatively immobile during devitrification (for example Nb, Ta, Th, Rb, Sc, Sr, Ba) exhibit high degrees of inter-element correlation. The abundances of these constituents are interpreted to reflect magmatic compositions. In contrast, relatively mobile elements (for example F, Cl, Sb, Sn, U) exhibit very low degrees of correlation (Duffield and Ruiz, 1992a). These constituents are more abundant in vitrophyre than in devitrified samples, and they probably were variably mobilized during devitrification. Much of the tin so mobilized was precipitated as cassiterite in the cool outer parts of devitrifying domes and flows, giving rise to minor tin deposits (Duffield and others, 1990).

Areal variations in concentrations of immobile trace elements form a quasi-random, rather than a regular, pattern throughout the lava field (Duffield and Ruiz, 1992a). Areal variations in phenocryst abundance and mean size exhibit a similar pattern. However, the life span of the lava field, as defined by $^{40}Ar/^{39}Ar$ ages and magnetic secular variation, indicates that the time period during which the magma reservoir was being tapped was shorter than that needed for the development of measurable chemical evolution; thus, chemical variations can be interpreted in terms of instantaneous monotonic vertical zonation of the magma reservoir (Duffield and Ruiz, 1992a,b).

For almost all constituents (exceptions include $^{87}Sr/^{86}Sr_i$, Sm, and Sc), the polarity of vertical zoning is opposite to the polarity reconstructed through the study of ignimbrites for other large-volume systems of silicic magma, as exemplified by the system that produced the Bishop Tuff, California (Duffield and Ruiz, 1992b). Nonetheless, mean concentrations and most inter-element correlations are the same for the Taylor Creek Rhyolite and the Bishop Tuff. The Taylor Creek Rhyolite apparently represents products from an ignimbrite-type zoned magma reservoir whose uppermost erupted part was variably contaminated by partial assimilation of roof rocks. Incorporation of about one weight percent of a Precambrian assimilant of broadly granitic composition could affect Taylor Creek Rhyolite magma enough to produce almost all of the observed chemical variations (Duffield and Ruiz, 1992a). Through such assimilation, concentrations of trace elements in uncontaminated Taylor Creek Rhyolite magma were moderated toward more common crustal abundances, while inter-element correlations were preserved.

In addition to robust correlations (some positive and some negative) with immobile trace elements, amount of assimilation correlates positively with $^{87}Sr/^{86}Sr_i$ and with the abundance and mean size of phenocrysts. Such correlations suggest that latent heat released during the growth of phenocrysts provided (at least in part) the thermal energy expended to power assimilation. The Sr-isotope ratio increased with assimilation, because the roof rock almost certainly was highly radiogenic Precambrian material (Duffield and Ruiz, 1992a).

High precision $^{40}Ar/^{39}Ar$ ages of sanidine phenocrysts indicate that all eruptions of Taylor Creek Rhyolite occurred in less than 100,000 yr at about 27.9 Ma (Duffield and Dalrymple, 1990). How much less is uncertain, but preliminary attempts to reconstruct the path of magnetic secular variation defined by the domes suggest that the eruptive period lasted a few thousand years or less (Champion and others, 1991).

All data for the Taylor Creek Rhyolite of which we are aware support a model wherein a single large-volume magma reservoir, chemically zoned with respect to trace elements, phenocrysts, and $^{87}Sr/^{86}Sr_i$, was tapped at least 20 times by vents distributed throughout an area of several hundred square kilometers. The Taylor Creek Rhyolite apparently provides a highresolution view of the uppermost part of this zoned reservoir.

PHYSICAL STRUCTURE OF THE DOMES

We have developed a general model for the structure of Taylor Creek Rhyolite lava domes from field observations, supplemented by comparisons of structure as depicted for other silicic lavas described in the literature. Our model is similar to that proposed by Christiansen and Lipman (1966, pl. 4) for a Tertiary rhyolite lava in central Nevada.

The model includes three principal elements: (1) pyroclastic deposits of an initial explosive phase, (2) a subsequently emplaced coherent, foliated dome, and (3) a flow-generated breccia that envelopes the foliated lava core (fig. 2). Most outcrops of the Taylor Creek Rhyolite represent parts of the coherent dome.

Duffield and Dalrymple (1990) reported that domes of the Taylor Creek Rhyolite, each conservatively reconstructed to a preerosion condition, range in volume from about 0.2 to 10 km^3, and that the total volume before erosion was about 55 km^3. Cumulatively, the preerosion volume (dense-rock equivalent) of genetically related pyroclastic deposits is judged to be roughly comparable to that of the domes themselves (Duffield and Dalrymple, 1990), although the proportion of dome lava to pyroclastic material may vary considerably from eruptive unit to eruptive unit throughout the lava field; for most units, exposures are too limited to accurately evaluate the situation. The principal effect of pyroclastic deposits on the physical character of an associated lava dome probably was to modify the configuration of the landscape over which the dome grew. This effect is thought to have had minor impact in shaping the structure of a typical Taylor Creek Rhyolite dome.

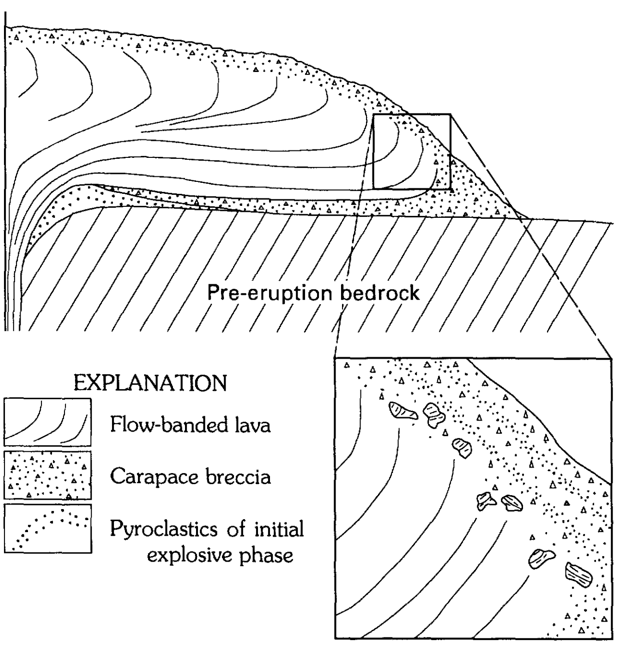

Figure 2. Idealized structural model of part of a dome of the Taylor Creek Rhyolite, as seen in cross section from vent to lateral margin. Relative volumes of pyroclastic and flow rocks may differ greatly from eruptive unit to eruptive unit. Enlarged view of snout of dome shows crude layering in flow breccia and pieces of flow-foliated lava incorporated into the breccia.

PYROCLASTIC DEPOSITS

Pyroclastic debris produced during the initial stage of each eruption of Taylor Creek Rhyolite magma was emplaced through fallout, flow, and surge mechanisms. Pyroclastic flows are by far the most voluminous pyroclastic rock type. Surge deposits are a very minor part of the pyroclastic sequence.

Individual pyroclastic flows generally are one to several meters thick, and locally they accumulated in sequences up to 70 m thick. All of the pyroclastic flows are nonwelded, or only weakly sintered, and consist almost entirely of pumice lapilli and ash of Taylor Creek Rhyolite; lithic clasts, both juvenile and foreign, are rare. The most voluminous sequence of pyroclastic flows produced during a single eruption is informally called the tuff of Garcia Ranch (Lawrence, 1985); this tuff is part of our map unit **Ttp**. It underlies the northernmost Taylor Creek Rhyolite dome near Indian Peaks (unit Tt_{20}), and is interpreted (Lawrence, 1985) to represent the initial pyroclastic phase of the eruption that produced this dome.

Pyroclastic fallout deposits occur in depositional units ≤2 m thick and form sequences as much as tens of meters thick. Though fallout clasts are mostly of Taylor Creek Rhyolite, foreign lithic fragments are locally abundant and probably represent products related to the process of opening a vent through preexisting Tertiary volcanic rocks. Fallout commonly drapes highly irregular surfaces, including the relatively steep flanks of slightly older domes of the Taylor Creek Rhyolite. Thus, initial depositional dips as high as 25° to 35° are common, as seen, for example, on the northwest and southwest flanks of dome Tt_9.

Fallout deposits range from nonwelded to thoroughly welded or agglutinated, reflecting differences in emplacement temperature and subsequent rate of cooling. Duffield (1990) described three locations where welding increases upward within conformable fallout sequences that grade imperceptibly into rocks that appear in the field and in thin section to be dome lava emplaced by routine nonpyroclastic effusion of magma. The field relations suggest that these rocks are the rhyolite equivalent of fountain-fed lava flows that are well documented and common in basaltic magma systems (Duffield, 1990).

None of the pyroclastic sequences shows evidence of a significant hiatus (for example, erosional channelling, soil development, and so forth) between depositional events or between the top of the sequence and overlying Taylor Creek Rhyolite lava. This characteristic suggests that any given pyroclastic sequence is of local origin and represents the initial stage of a geologically short-lived eruption whose dome lava quickly covered (at least in part) and preserved pyroclastic debris produced during the initial stage of eruption.

Some pyroclastic deposits that overlie Taylor Creek Rhyolite domes locally are in direct contact with flow-foliated lava rather than flow breccia, which suggests that breccia did not form over the entire surface of all domes, or that breccia was eroded locally between some pairs of dome-forming eruptions, or both.

Due to erosion and partial cover by deposits younger than the Taylor Creek Rhyolite, few of the pyroclastic units or groups of units that form recognizable sequences can be traced more than a kilometer or two in the field. The tuff of Garcia Camp (part of map unit **Ttp**) crops out continuously for several kilometers, but positive correlation of it, the most voluminous of the Taylor Creek Rhyolite pyroclastic flows, with other nearby similar but isolated exposures is frustrated by lack of outcrop continuity and by close petrologic and chemical similarity among all Taylor Creek Rhyolite pyroclastic flows.

Eggleston (1987) suggested that most Taylor Creek Rhyolite pyroclastic flows are a time-stratigraphic unit. In light of this suggestion (see Eggleston, 1987, geologic map), field relations would require that domes of Indian Peaks, House Tank, and Exit Tank (units Tt_{20}, Tt_{15}, and Tt_{13},) are younger than domes of Long ridge, Bear hill, Springtime Canyon, Squaw Creek, Boiler Peak, Water Canyon, and Adobe Canyon (units Tt_{19}, Tt_{18}, Tt_{17}, Tt_{16}, Tt_9, Tt_{12}, and Tt_{14},). Verification of most of these age relations among the domes is impossible for lack of appropriate exposures. We prefer to interpret most Taylor Creek Rhyolite pyroclastic deposits as locally produced and deposited, in concert with our general structural model of dome emplacement (fig. 2) and with the observation that at least the thoroughly agglutinated deposits had to be of local origin for thermal considerations alone (Duffield, 1990).

COHERENT CORE OF A DOME

Almost all outcrops of the Taylor Creek Rhyolite represent the coherent lava part of the general structural model (fig. 2). The thickest continuous exposure within a single eruptive unit is in the dome at White Water Canyon (unit Tt_7), where 300 m of flow-banded rhyolite forms the south wall of Taylor Creek; the base of this unit is not exposed.

Most of the Taylor Creek Rhyolite lava is flow foliated, although foliation locally is only weakly developed or absent at the outcrop scale, which typically is at least decameters in extent. Foliation is expressed as a physical parting or weakness commonly etched out by weathering and is defined by open spaces (vesicles?, gash fractures?), or a relatively high concentration of phenocrysts, or both. Foliation surfaces are less than one centimeter to about one meter apart.

The orientation of foliation varies from constant over distances of decameters to highly contorted over distances of centimeters. The first-order pattern of foliation in plan view is observably concentric to the lateral margins and vent of some eruptive units, a situation that probably is general but is not demonstrable for all mapped units. This structural pattern is best illustrated in aerial photographs of map unit Tt_7, whose foliation focuses on the northeast end of the outcrop area and parallels the breccia-defined preerosion lateral margins of the 6-km-long flow. More complex foliation patterns presumably reflect local flow conditions that deform the first-order pattern.

Interpretation of the structural position of specific outcrops suggests a few generalizations about spatial variations in the orientation of first-order foliation within a dome (fig. 2). A basal zone is characterized by subhorizontal foliation. In contrast, foliation commonly fans from moderate to steep dips within the upper parts of a dome (fig. 3); foliation tends to steepen upward and inward toward the vent of a dome and locally passes to an "overturned" orientation. The contact between steeply and gently dipping structural domains may be abrupt, although field exposures are inadequate to test this suggestion. Foliation that fans steeply across a vertical orientation has been misinterpreted as indicating a vent area by some workers in the Taylor Creek area (Fries, 1940; Rye and others, 1990).

We interpret foliation to be the product of differential lamellar flow within the moving liquid core of a growing eruptive unit. Christiansen and Lipman (1966) suggested that foliation originates in or at the vent during magma extrusion and then is carried within the body of a moving flow to its final emplacement position. We suggest that foliation also forms, or at least is deformed, away from the vent during movement within the body of a growing dome. Fink (1983) arrived at a similar conclusion from his detailed structural study of the rhyolite lava flow at Little Glass Mountain in northern California. Structural complexity in the Taylor Creek Rhyolite indicates that early formed foliation can be folded and refolded, without being disrupted by the formation of new foliation across preexisting foliation surfaces.

We infer that the relation between the orientation and depth of "first-order" foliation within a dome reflects the variable yet broadly overriding effect of gravitional pull on a spreading viscous body. Foliation is roughly flat where the viscous liquid spreads under considerable load, whereas foliation tends to ramp steeply upward near and at the virtually unloaded free upper surface of a dome. Lateral buttressing provided by a thickening wedge of flow breccia at the snout of a dome favors differential upward movement at the top of a growing body and thus produces the fan structure noted above (fig. 3).

Locally, flow foliation is only weakly developed or not recognizable over areas of hundreds of square meters. Such areas tend to be in the central parts of eruptive units and at moderate to deep structural

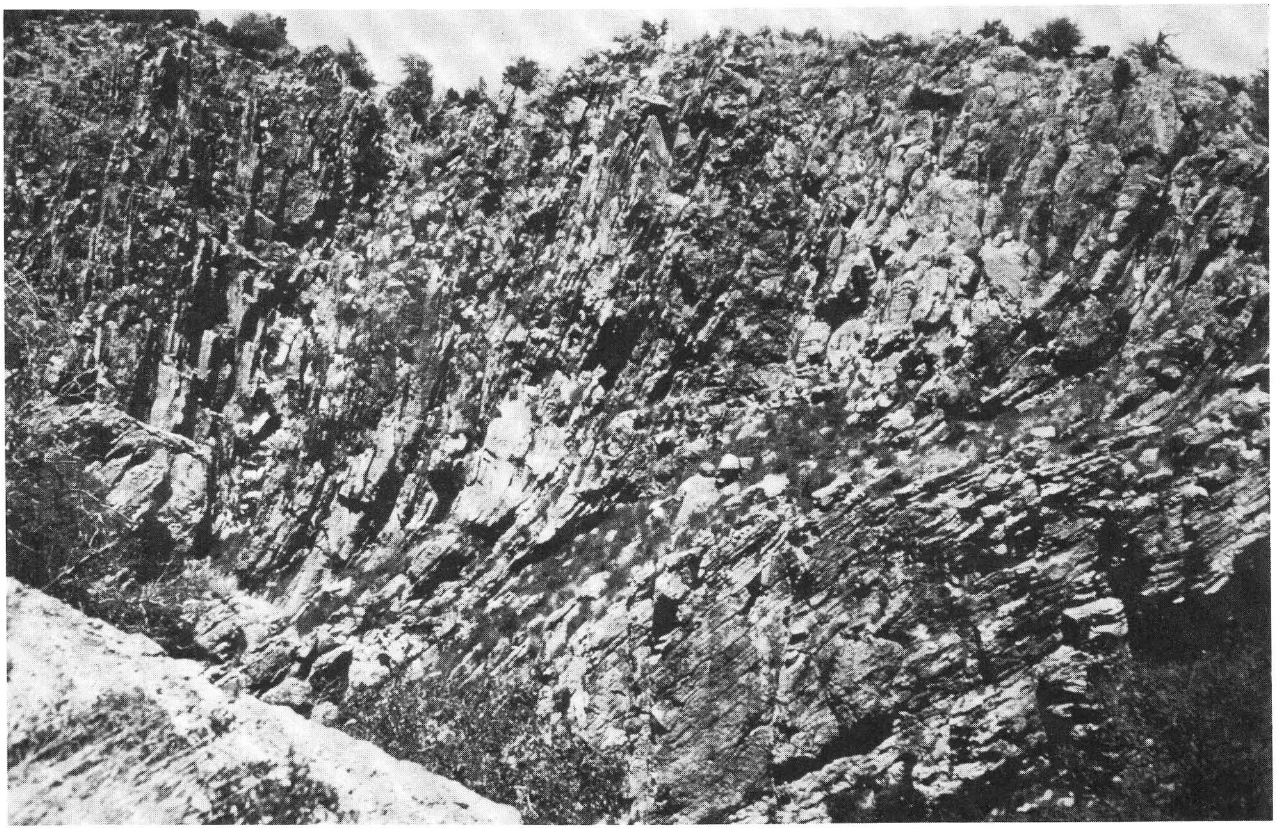

Figure 3. Flow-foliated lava exposed in canyon wall of Taylor Creek at southernmost outcrop of map unit Tt_4. Vertical relief is about 35 m. Lateral component of flow during emplacement is interpreted to have been from left (north) to right (south). Compare with figure 2.

levels. As such, they may represent zones that stayed hot and fluid long enough after emplacement was complete to permit structural homogenization and annealing of foliation developed during earlier flowage.

The fabric of virtually uneroded brecciated surfaces of Quaternary rhyolite lava domes and flows at Newberry Caldera, Oregon, and Medicine Lake and Mono Craters/Long Valley, California, suggests that the plan-view pattern of flow structures which developed within the viscous body of domes like those at Taylor Creek can be transmitted upward into overlying flow breccia. These uneroded lavas generally exhibit brecciated upper surfaces corrugated concentrically to their vents and parallel to lateral flow margins. Alternatively, Fink (1984) suggested that such corrugation forms through folding caused by horizontal compression, apparently unrelated to the differential upward ramping of viscous lava envisioned herein. Perhaps both mechanisms are effective.

FLOW BRECCIA

Each dome of the Taylor Creek Rhyolite is interpreted to have become enveloped, or nearly so, by flow-generated breccia during emplacement. This breccia is simply the rhyolitic equivalent of breccia that envelopes basaltic aa, which forms because the relatively cool and brittle skin of a flow breaks in response to inflation and flowage of a viscous liquid core. Lateral advance of the liquid core causes a flow to override its breccia, which thus becomes the bottom of the breccia envelope. In spite of considerable erosion during the nearly 28 m.y. since eruptions of the Taylor Creek Rhyolite, remnants of flow breccia are preserved and reasonably well exposed on all but four (Tt_4, Tt_{11}, Tt_{13}, and Tt_{15}) of the eruptive units. The thickness of breccia remnants along lateral margins of domes ranges from a few meters to as much as 90 m. Basal breccia, which is uneroded where overlain by the source dome, is typically 5 to 15 m thick.

Flow-generated breccia typically is an unsorted mixture of multimeter-wide blocks and progressively smaller fragments down to ash size. Clast-supported deposits with interclast voids are common. The upper limit on block size is difficult to define, because breccia grades into a coherent flow-foliated body, which is the source of the blocks. The proportion of relatively small fragments probably is a function of the duration of movement and degree of tumbling that occurred during breccia formation and accumulation.

Figure 4. Panorama of crudely layered flow breccia at the west snout of map unit Tt_7 exposed in canyon of Taylor Creek. Layering dips about 30° left (west) off coherent flow-foliated lava that advanced from east to west during formation of this lava flow. Maximum height of outcrop is about 60 m. Rocks that form hills in left background postdate Taylor Creek Rhyolite.

Crude layering is locally present within flow breccia at and near the lateral margins of domes (figs. 2, 4). This layering is defined by deposits a few to several meters thick, which are separated by subtle discontinuities in fragment size along planes commonly etched preferentially by weathering. Layers dip from about 25° to 35° away from the source dome. The layering is interpreted to form from repeated gravity-driven debris avalanches as breccia becomes oversteepened at the advancing lateral margin of a dome. Dip presumably reflects the angle of repose for this type of deposit.

For isolated deposits of flow breccia, the orientation of layering provides information about the lateral direction from which breccia formed and can thus help identify the source dome. For example, in the southernmost part of the map area north-dipping layering in breccia of Taylor Creek Rhyolite now isolated by erosion and faulting indicates almost certain correlation with the eruptive unit at Running Water Canyon (Tt_2) directly to the south.

The Taylor Creek Rhyolite exhibits so little petrologic and geochemical variation (Duffield and Ruiz, 1992a) that the orientation of layering in flow breccia may be the sole constraint for locating contacts between eruptive units within areas of continuous exposure of breccia from multiple sources. For example, the boundary between areas of north and southwest dip for layering within breccia associated with eruptive units at Boiler Peak (Tt_9) and at Alexander Peak (Tt_8) accurately locates the contact between these domes. Similarly, the boundary between adjacent areas of different dips within continuous exposure of flow breccia between eruptive units White Water Canyon (Tt_7) and Cabin Tank (unit Tt_6) accurately locates the contact between these domes.

Field observations suggest that structural and textural contrasts are sometimes recognizable between breccia at the base and breccia on the flanks and top of a dome. The recognition of basal versus higher-level breccia is straightforward when the source dome and breccia are preserved and exposed together. However, correct interpretation of the intradome structural level represented by isolated outcrops of breccia can be complicated if not impossible without guidelines to features that may reflect the different structural settings.

The principal contrasts that we have observed presumably reflect relatively slow cooling beneath a hot dome as opposed to relatively quick cooling under little or no load at the lateral and upper margins of a dome. The process of loading and perhaps even the static load could result in fragmentation and an increase in the proportion of small clasts; partial or extreme welding also could occur if the time-integrated history of load and temperature was appropriate. The environment at and near the thinning edge of a dome presumably grades into conditions for breccia typical of lateral dome margins and thus could produce basal breccia indistinguishable from its structurally higher counterpart in isolated outcrops.

Characteristics of the Taylor Creek Rhyolite that may relate to spatial variations in load and temperature are that basal breccia tends to have a smaller average clast size and to include less open space between clasts, relative to counterparts at higher structural levels. Little or no welding is apparent, as clasts tend to be equant rather than flattened, although basal breccia tends to form a denser, more coherent deposit.

Contact relations with adjacent lava also can help guide assignment of flow breccia to a basal or higher structural level. Because breccia becomes a basal deposit as a dome advances laterally in caterpillar-tractor fashion over its own tumbled debris, the contact between basal breccia and its source dome tends to be relatively sharp. In contrast, the contact between the coherent foliated part of a dome and its breccia cap tends to be a thick irregular zone within which blocks of flow-foliated lava were detached from the dome and tumbled and broke as they were incorporated into the breccia. Crude layering seems to be restricted to the lateral margin of a growing dome, where the angle of repose is repeatedly exceeded.

A ubiquitous flow foliation recognizable within virtually all but the smallest fragments in flow breccia of the Taylor Creek Rhyolite distinguishes the breccia from fragmental deposits of other origins. The presence of foliation in breccia fragments, though tumbled to diverse orientations, attests to a history of differential flow as a viscous liquid before solidification, brittle failure, and incorporation of fragments into a developing breccia envelope. In contrast, most clasts of the Taylor Creek Rhyolite in deposits of the initial pyroclastic phase of an eruption are not internally flow foliated.

We know of one location where a deposit of moderately agglutinated fragments of the Taylor Creek Rhyolite has been interpreted as basal flow breccia (Lawrence, 1985, fig. 2–5), though the fragments are massive and unfoliated internally. We interpret this deposit as agglutinated fallout from lava fountains, and Duffield (1990) described evidence that the deposit is part of an agglutinate cone built around a central vent.

FLOW FOLIATION AND STREAM EROSION

Taylor Creek and its tributary in Paramount Canyon flow west-southwestward across the south-central part of the Taylor Creek Rhyolite lava field. Along most of this 25-km reach of the drainage, these streams are located very near contacts between overlapping pairs of domes and are systematically slightly within the older dome of each pair. We believe that this situation reflects control of the lateral component of stream erosion imposed by steep flow foliation in coherent rhyolite lava of the older dome of each pair.

The surface upon which the Taylor Creek Rhyolite domes were emplaced was relatively planar and roughly horizontal, as shown by roughly concordant elevations of the dome bases and the roughly equant plan-view shapes of most of the domes. Flow that

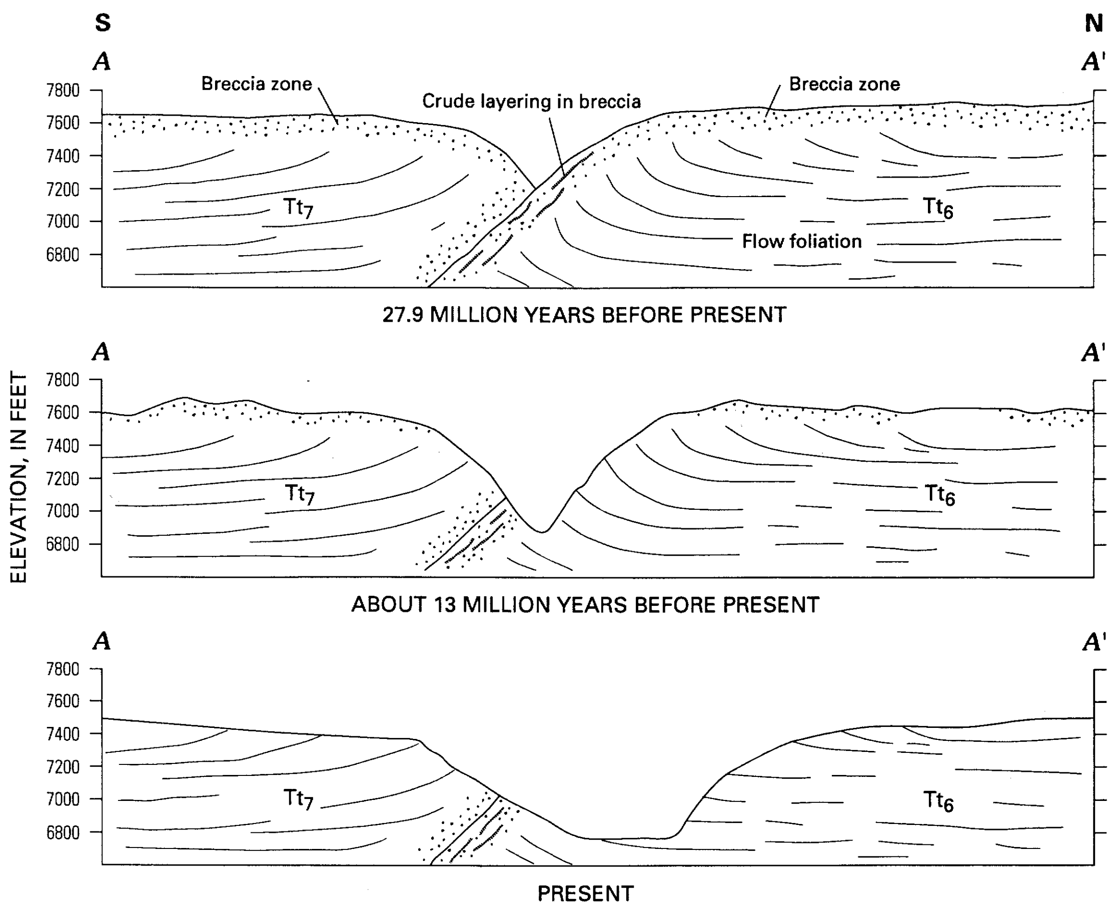

Figure 5. Time series of a north (*A'*) south (*A*) cross section across the canyon of Taylor Creek where it flows between eruptive units Tt_6 and Tt_7. Instead of following zone of relatively friable interdome breccia during downcutting, the lateral trajectory of Taylor Creek appears to have been guided by steep flow foliation in unit Tt_6. The situation at 13 Ma assumes a constant rate of erosion since 27.9 Ma.

occurred during emplacement of the 6-km-long eruptive unit Tt_7 indicates at least a locally southwestward-sloping land surface. A ubiquitous gentle dip to the west-southwest for ignimbrites of Taylor Creek Rhyolite records minor posteruption regional tilt that may have occurred shortly after 28 Ma (Cather, 1990).

The Taylor Creek Rhyolite apparently never was entirely buried by younger rocks. A slightly younger ignimbrite of regional extent, the Bloodgood Canyon Tuff (Ratté and others, 1984), locally ponded in topographic lows within the rhyolite dome field, and still younger mafic lavas similarly ponded and partly covered some of the Taylor Creek Rhyolite domes (Richter, 1978; Richter and others, 1986a,b; Lawrence and Richter, 1986). However, the only volumetrically significant deposits that postdate the Taylor Creek Rhyolite in the area are alluvia derived mostly from the domes themselves. The Taylor Creek Rhyolite was in effect partly buried in its own detritus shortly after emplacement, although the tops of most of the domes remained exposed as source areas for the detritus.

We interpret these features to indicate that Taylor Creek is a consequent stream, whose initial course was controlled by constructional topography created principally by Taylor Creek Rhyolite volcanism and whose plan-view shape has changed little with time. We submit that much of the course of Taylor Creek became localized in valleys formed between steep flanks of pairs of adjacent domes, and that subsequent erosion into the rhyolite has been almost entirely vertical (as much as 300 m).

This proposed history for Taylor Creek is illustrated with a time series of roughly south-north vertical sections that cross the contact between units Tt_6 and Tt_7 (fig. 5). The landscape immediately after emplacement of these two domes would have included a steep-sided valley, exactly along their contact, whose walls might have sloped about 35°, the approximate angle of repose for flow breccia. Early Taylor Creek occupied this valley (fig. 5, 27.9 Ma). As erosion proceeded, the axis of Taylor Creek lowered into eruptive unit Tt_6 (fig. 5, about 13 Ma), the older of the two domes, even though one might have anticipated that the axis would follow a south-plunging trajectory of little resistance within the zone of relatively friable breccia between domes Tt_6 and Tt_7. Instead, erosion was principally vertical, presumably because steeply dipping foliation in coherent lava of dome Tt_6 contained lateral erosion once the breccia was cut through.

This history of erosion, which may have general application beyond the Taylor Creek region, leaves the zone of flow breccia along the contact between pairs of domes perched on stream-canyon walls, a fact that can cause confusion during field mapping. For example, a study of aerial photographs carried out before field work led us to conclude that an almost perfectly regular 100° arc traced within rhyolite by Taylor Creek (near and parallel to the contact between domes Tt_6 and Tt_7) would be in breccia, exactly along a contact between two eruptive units. To the contrary, the breccia was discovered perched scores of meters above the stream on the south wall of the canyon, a discovery that guided and facilitated later mapping of similar structural situations upstream.

ENDOGENOUS VERSUS EXOGENOUS GROWTH

Field relations suggest that each mapped dome represents an eruptive unit, that each of these units was emplaced from its own vent, and that each vent was active only once during a geologically brief period. Field relations strongly suggest that each eruption went through the same unidirectional sequence of events that began with the production of pyroclastic deposits, followed closely in time by the quiet effusion of magma to form a breccia-enveloped dome. Some of the earliest-formed coherent dome material in such a sequence might have been destroyed by explosive vent activity, an idea consistent with the sparse presence of dense lithic clasts of the Taylor Creek Rhyolite in some pyroclastic deposits. However, the rocks preserved as the Taylor Creek Rhyolite domes suggest a rather simple and uniform unidirectional sequence of eruptive stages. The Taylor Creek Rhyolite thus is interpreted to present examples of endogenous domes, that is, domes that grew largely if not entirely from within rather than by significant contributions from both internal and external accumulation of effusive lava.

If an eruption of Taylor Creek Rhyolite magma had fluctuated repeatedly between endogenous and exogenous styles, as is typical of the historically active dacitic domes at Mount St. Helens, Washington (Swanson and Holcomb, 1990), and at Santiaguito, Guatemala (Rose, 1987), one would expect to find multiple zones of flow breccia sandwiched within flow-foliated coherent lava. Though erosion could have removed the evidence for some examples of such structure, it seems unlikely that all would be so destroyed. The only possible examples found during our mapping are within map units Tt_8 and Tt_9, where several decameter-sized outcrops of breccia are nearly surrounded by flow-foliated lava. An interpretation consistent with purely endogenous growth is that erosion has begun to locally reach the zone of basal breccia. The bottoms of these eruptive units are nowhere exposed, but the areas of breccia are at low structural levels in what may be relatively thin marginal lobes of the domes. However, if these outcrops of breccia indeed reflect mixed endogenous and exogenous growth, they are exceptional examples within an extensive field of lava domes. Many kilometers of field traverses across the interiors of eruptive units revealed no other examples of breccia within flow-foliated lava.

VENT LOCATION AND MIGRATION

The accuracy with which dome vents are locatable in plan view varies from excellent for a few to moderate for most to poor for a few, although each vent except one (that for unit Tt_4) can reasonably be construed to lie within the present outcrop area of its erupted lava.

Evidence that vents are within present outcrop areas, even if no other information suggests a more precise location, is provided by the distribution of flow breccia around the lateral margins of eruptive units. Though this breccia crops out discontinously, the field evidence virtually requires that vents for domes Tt_2, Tt_7, Tt_8, Tt_9, Tt_{12}, Tt_{17}, Tt_{18}, and Tt_{19} are within areas of their flow-foliated lava and suggests the same interpretation for domes Tt_1, Tt_{14}, and Tt_{16}.

Additional evidence for the positions of what are judged to be the most accurately located vents is provided by a tightly focused concentric pattern of flow foliation. This pattern is well displayed in aerial photographs of domes Tt_3, Tt_7, and Tt_{18}. Other less well documented examples are exhibited by domes Tt_8, Tt_9, and Tt_{10}. In addition, the map shape of dome Tt_6 is nearly semicircular and convex southwestward, and this dome displays a pattern of flow foliation that focuses on the center of the arc for the half circle. Perhaps dome Tt_6 grew radially outward from a central vent along a southwest-facing fault scarp to produce such outcrop and foliation patterns; alluvium younger than Taylor Creek Rhyolite covers the area where the hypothetical fault or the missing half of a hypothetical circular dome might be present.

Judging by the shapes of Quaternary silicic domes elsewhere, one might reasonably generalize that the highest part of any rhyolite dome is above the vent area immediately after emplacement; relatively minor collapse localized directly over a vent at the end of eruption could indent this high area. For domes of the Taylor Creek Rhyolite the most accurately located vents typically are in the topographically highest part of each eruptive unit. Accordingly, we suggest that the topographically highest part of a Taylor Creek Rhyolite dome today approximately marks the preerosion vent position, because erosion has been dominantly vertical rather then lateral. This suggestion implies that the vent for dome Tt_5 is in the east-central part of its outcrop area and that the vent for dome Tt_4 is buried beneath a thin cover of younger rocks at a topographic high centrally located with respect to several isolated outcrops of Tt_4 distributed within a roughly circular 5-km-wide area.

Evidence is equivocal for constraining the positions of vents for eruptive units Tt_{13} and Tt_{15}. For Tt_{13}, a 1-km-long dike of Taylor Creek Rhyolite crosscuts the base of, and merges upward with, the eruptive unit. This dike is interpreted to be part of the vent system for Tt_{13}, but where the dike intersected the ground surface during eruption is unknown.

Duffield (1990) summarized evidence that precisely locates a partly eroded cone of agglutinate built around a vent for dome Tt_{20}. He also described similar though less compelling evidence for another vent, about 5 km to the northwest, that may also have erupted part of dome Tt_{20}, the most voluminous of the map units. Interpretation of dome Tt_{20} as a single eruptive unit (Duffield and others, 1987) is complicated by the fact that erosion has created many isolated outcrops whose reconstruction as a single unit is equivocal.

Within the framework of uncertainties described above, we have constructed a map that portrays vent migration within clusters of overlapping domes whose relative ages are known (see map sheet). Migration within a cluster is variably eastward and westward, and always with a net northward component. The pattern of vent migration with time throughout the dome field cannot be defined unambiguously for lack of information about relative ages for domes that are not in contact.

McIntosh and others (1990) have shown that vents for large-volume ignimbrites of the Mogollon-Datil volcanic field as a whole migrated from southeast to the north and west as the field grew between 36.2 and 24.3 Ma. Perhaps groups of vents for the Taylor Creek Rhyolite, located in the east-central part of the Mogollon-Datil volcanic field, mimic this migration, though greatly telescoped in space and time. Because the Taylor Creek Rhyolite dome field probably formed in a few thousand years or less and thus probably within a uniform stress regime, it seems reasonable for vent migration to have been unidirectional.

STRUCTURAL CONTROL OF VENTS

Direct field evidence about structural controls on the position and distribution of vents for the Taylor Creek Rhyolite is practically nonexistent. With the exception of a dike in eruptive unit Tt_{13}, the shallow roots of vents are not exposed. We infer that the upper crustal conduits for Taylor Creek Rhyolite magma were tabular, whether planar or gently curved. Such conduits for magma in the upper crust are common worldwide as indicated by hosts of dikes exposed as feeders for volcanic rocks—mafic, intermediate, and silicic alike. Concentrated vertical flow of magma may develop locally along a dike (Delaney and Pollard, 1981) so that both fissure and central vents are possible eruption modes for magma fed through dikes in the upper crust.

The dike that is interpreted to be part of the shallow feeder system for eruptive unit Tt_{13} is gently sygmoidal and trends generally north-northeast. About 8 km to the south-southwest, a fault of this same orientation offsets part of eruptive unit Tt_{12}, and a series of en echelon stream reaches nearby within unit Tt_{12} suggests fault control, also of this orientation. These indicators of stress may reflect maximum horizontal compression of roughly north-northeast direction that controlled the emplacement of a swarm of dikes which fed all eruptions of the Taylor Creek Rhyolite (fig. 6A).

A few other north-northeast-trending faults offset the Taylor Creek Rhyolite, but whether these reflect the orientation of crustal stress during growth of the lava field or only at a later time is uncertain. Most other faults that offset the Taylor Creek Rhyolite trend

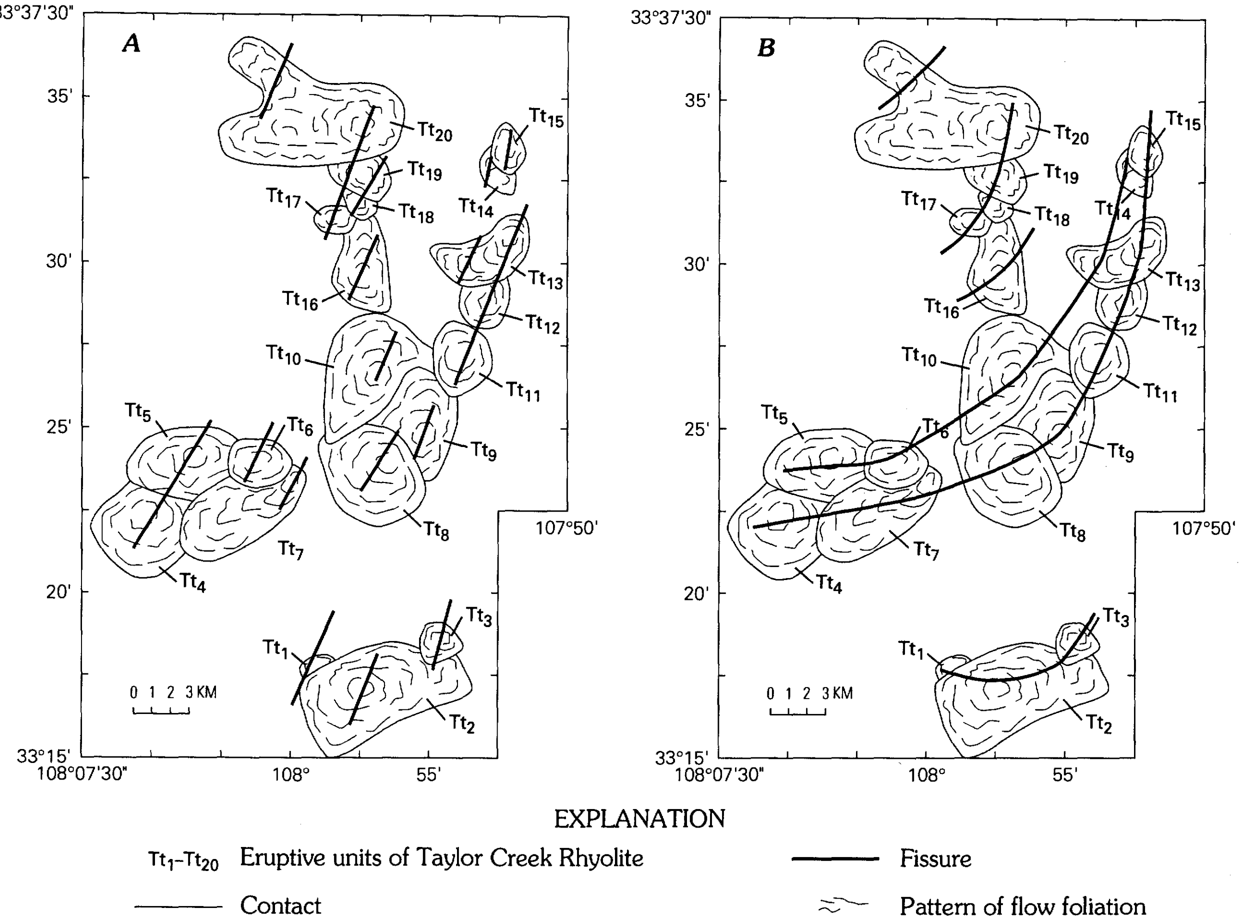

Figure 6. Hypothetical fissure systems along which vents for Taylor Creek Rhyolite might have been located. ***A***, North-northeast-trending fissures, parallel with dike of Taylor Creek Rhyolite (unit Tt_{13}, map sheet) and possible orientation of maximum horizontal stress during late Oligocene time. ***B***, Arcuate fissures, consistent with a point source of stress whose focus is a large reservoir of Taylor Creek Rhyolite magma.

approximately northwest. There are no known dikes of the Taylor Creek Rhyolite with this trend. Cather (1990) described a broadly north-trending axis of maximum horizontal stress in a regime of east-west crustal extension for this part of New Mexico during Taylor Creek Rhyolite time.

Time-space-volume-composition relations suggest that all eruptions of the Taylor Creek Rhyolite were fed from a single reservoir of magma at least 30-km wide (Duffield and du Bray, 1990; Duffield and Dalrymple, 1990; Champion and others, 1991; Duffield and Ruiz, 1992a), comparable in size to nearby calderas of the Mogollon-Datil volcanic field. As evidenced by these calderas, magma bodies of this size locally created centrally focused stress fields, overprinted on regional stress, and gave rise to systems of ring fractures. The distribution of vents for the Taylor Creek Rhyolite defines six loci of arcuate trace with a common focus northwest of the Taylor Creek Rhyolite area (fig. 6B). While intellectually satisfying in terms of simplicity of fracture pattern related to a "point source" of stress, field exposures are lacking of arcuate faults that might have controlled the distribution of vents. Moreover, the focus of this hypothetical arcuate structure is many kilometers northwest of the Taylor Creek area. The issue of structural control of vent locations remains unresolved. Perhaps both arcuate and linear fissures are involved. We favor a model dominated by north-northeast-trending linear fissures along which central vents were active for many if not most of the eruptions (fig. 6A).

COOLING TIMES AND DURATION OF VOLCANISM

The combined evidence from $^{40}Ar/^{39}Ar$ age determinations of sanidine phenocrysts and the reconstructed path of magnetic secular variation recorded in the domes suggests a mean intereruption interval on the order of 100 yr, on the assumption that the 20 known eruptions occurred serially. Independent evidence of cooling histories constrains minimum intereruption intervals for two pairs of overlapping domes.

Duffield and others (1990) described a process of tin automineralization that affected the Taylor Creek Rhyolite. Tin was released from the hot core of a dome as it cooled, degassed and devitrified; was carried outward in a vapor phase; and was redeposited in the cooler outer part of the same dome. Duffield and others (1990) also noted two localities where this sort of mineralization was completed in the older of pairs of overlapping domes, before eruption of the younger dome. Because the process of automineralization is driven by thermal energy released as a dome cools to ambient temperature, the minimum intereruption interval is the cooling time of the older dome for these pairs.

Manley (1989) developed a method to calculate temperature profiles through a body of silicic lava as a function of time since its emplacement. In addition to conductive cooling, this method includes adjustments for thermal energy released by devitrification of glassy groundmass (virtually all groundmass of the Taylor Creek Rhyolite devitrified during initial cooling to ambient temperature) and thermal energy convected out of a cooling body by circulating rainfall and snowmelt.

We applied Manley's calculation to two domes of the Taylor Creek Rhyolite, one 350 m and the other 100 m thick, that approximately encompass the entire range of thicknesses for the dome field. Initial temperature is set at 800°C, the approximate temperature of phenocryst growth (Duffield and du Bray, 1990). Emplacement of a typical dome is assumed to have been instantaneous, although a period of decades might be more appropriate. Errors associated with this assumption and with a uniform instantaneous emplacement temperature of 800°C are mutually offsetting, though of unknown magnitudes. Mean annual precipitation during late Oligocene time in the Taylor Creek Rhyolite area is unknown but is assumed to be 40 cm. Thermal consequences of the adjustment for precipitation are a second-order effect. With such limitations in mind, a calculated time series of temperature profiles indicates that the thinnest and thickest domes would have cooled to near ambient conditions in about 150 yr and 1,000 yr, respectively (fig. 7).

If the mean cooling time of an "average" Taylor Creek Rhyolite dome was about 500 yr, and if 20 eruptive units cooled serially, each to near ambient temperature just before the next eruption began, then the lifespan of the dome field was about 10,000 yr. This duration is well within that suggested by the $^{40}Ar/^{39}Ar$ results (Duffield and Dalrymple, 1990) but is longer than that suggested by magnetic secular variation (Champion and others, 1991). Thus, an implication of the magnetic results interpreted within the framework of the calculated mean cooling time is that some eruptions were simultaneous. Field evidence is permissive but does not require such an interpretation. Simultaneous eruptions and subsequent periods of cooling require fewer than 20 unique paleomagnetic directions, which is consistent with the magnetic data.

The largest number of eruptive units within a single stratigraphic cluster is five (Tt_{16}, Tt_{17}, Tt_{18}, Tt_{19}, and Tt_{20}). These could have been erupted in about 2,000 yr, the approximate total time required for four successive intereruption periods of cooling to near ambient temperature. Because examples of the tin automineralization as described earlier are absent within this cluster and thus cooling to near ambient temperature is not required between eruptions, the five domes could have grown in somewhat fewer than 2,000 yr. Therefore, if serial eruptions within this stratigraphic cluster were contemporaneous with serial eruptions within the other five stratigraphic clusters, the entire dome field could have formed in somewhat fewer than 2,000 yr. Such a brief period is consistent with that indicated by magnetic secular variation, within the uncertainties associated with the magnetic- and thermal-history analyses.

CONCLUSIONS ABOUT THE TAYLOR CREEK RHYOLITE

Most of the Taylor Creek Rhyolite domes and flows were emplaced through the quiet effusion of magma; three eruptions were at least in part characterized by lava fountaining that produced substantial agglutinate but no unequivocal dome lava (Duffield, 1990). A typical eruption followed a unidirectional sequence from an initial pyroclastic phase to a quietly effusive phase, with apparently no intervening hiatus and during a geologically brief period. All eruptions were fed from a single reservoir of magma. Very likely some of the 20 known eruptions occurred simultaneously, rather than serially, for the lava field as a whole. The entire lava field probably formed in a few thousand years or less.

Growth of a typical dome was endogenous and produced a flow-foliated coherent lava core enveloped by flow-generated breccia. Gravity-driven debris avalanches at the advancing steep lateral margin of a dome resulted in crude layering of the breccia there.

Eruptive activity as charted by vent locations migrated irregularly northward within clusters of overlapping domes whose relative ages are known. Central vents probably are located along dikes, but whether the dike fissures are linear, arcuate, or both is unknown.

GENERAL DISCUSSION OF SILICIC DOMES

Williams (1932) wrote the first comprehensive and systematic review of volcanic domes in the early 20th century. Following a few decades of only sporadic studies of such silicic lavas, considerable interest in silicic domes was rekindled in 1980 with the onset of dome formation at Mount St. Helens and with the unparalleled opportunities there for detailed documentation of dome growth. This renaissance quickly resulted in the publication of at least two special volumes devoted to

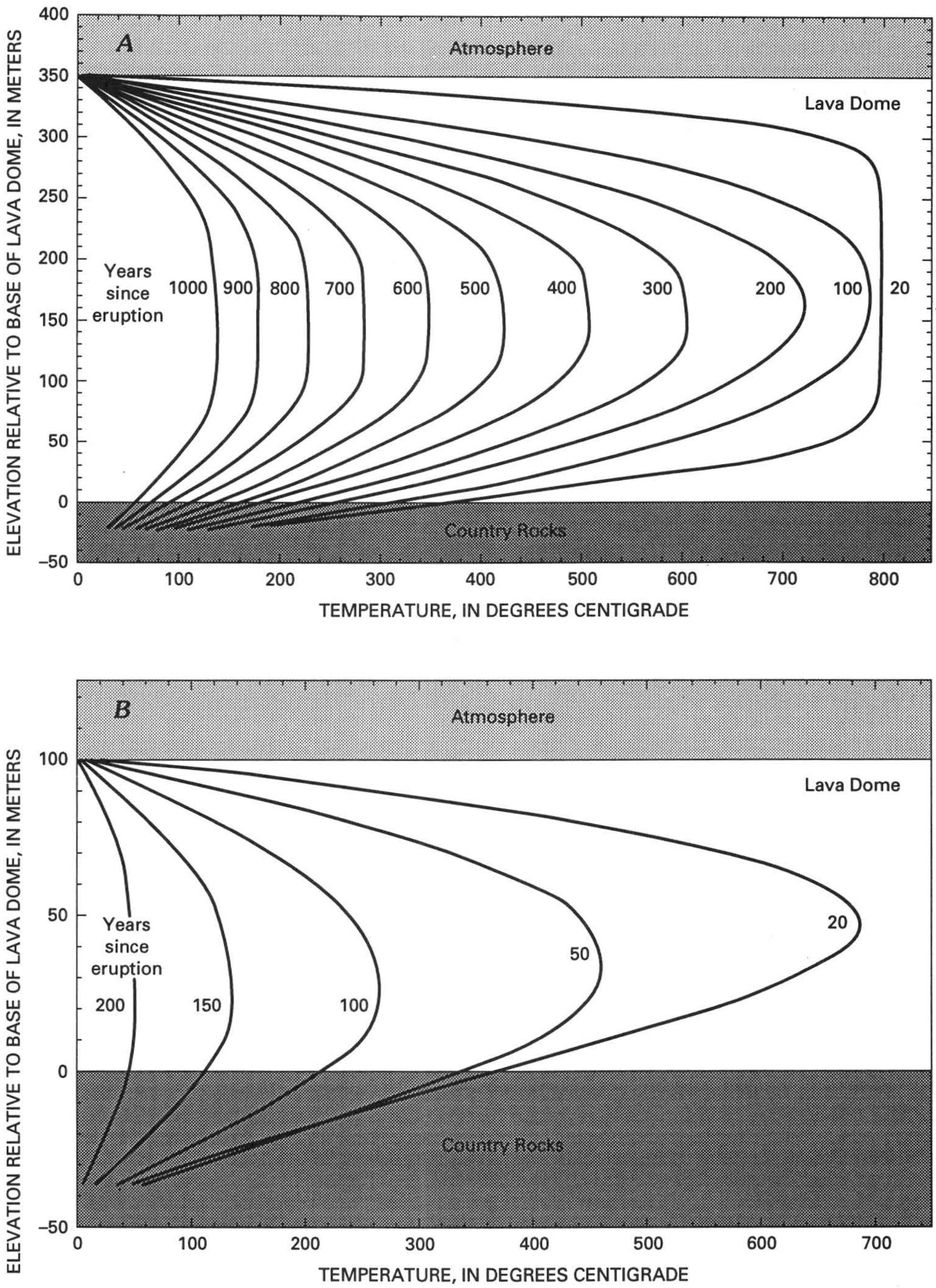

Figure 7. Time series of temperature profiles through ***A***, thickest and ***B***, thinnest domes of the Taylor Creek Rhyolite. Calculated by the method of Manley (1989).

lava domes and flows (Fink, 1987, 1990). Nonetheless, many structural features observed to develop in silicic domes during their growth do not readily relate to structures exposed in eroded analogs of the prehistoric geologic record. Generalizations about structures and textures and their distribution within silicic domes are difficult to establish from information now available.

Erosion greatly complicates attempted comparisons between the youthful and older domes. In younger domes, only the outermost surface generally is available for direct study, whereas older domes generally are exposed mostly or only at deeper structural levels. For example, Fink (1983, 1984) and Fink and Manley (1987) have characterized in detail the structural and textural zones exhibited on the surfaces of several Holocene rhyolite domes in the Western United States. Drilling has permitted a drill-core view across one of the studied domes (Manley and Fink, 1987). Yet general findings that might transfer to the study of such domes as those at Taylor Creek are difficult to document. While the Holocene domes exhibit a remarkable variety of outer-surface structures and textures, the original outer surface of a typical Taylor Creek Rhyolite dome is almost, if not entirely missing. Erosional remnants of flow breccia define the outermost structural zone preserved, but this zone lacks the variety and fineness of structure and texture of the outer surfaces of Holocene counterparts. In contrast, outcrops of the Taylor Creek Rhyolite provide considerable information about the structure of the flow-foliated core of domes, while possible analogous structure in uneroded domes is mostly a subject of speculation. With such caveats in mind, we speculate on generalizations that may apply to silicic domes.

We suggest that there is a tendency for endogenous growth to correlate with high SiO_2 content of magma erupted as domes. This suggestion is impossible for us to verify, because the internal structure of many domes is poorly exposed or unexposed. Nonetheless, the uniformly rubbly outer surfaces of young rhyolite domes of which we are aware imply a simple endogenous origin. The only historically emplaced rhyolite dome of this type is that at Novarupta, Alaska. Geologically youthful but prehistoric rhyolite domes at such locations as Yellowstone Caldera, Wyoming, Valles Caldera, New Mexico, the Long Valley Caldera-Mono Lake area, California, and the Three Sisters area, Oregon also appear to be uniformly enveloped in flow breccia. We also recognize that volatile-rich magma (or magma erupted through voluminous shallow ground water) of whatever composition results in pyroclastic volcanism at the expense of dome formation.

Most domes of dacitic composition apparently are of mixed endogenous and exogenous origins. Mount St. Helens, Washington, and Santiaguito, Guatemala, are two well-documented historic examples in volcanic arcs along continental margins. Domes of both structural types occur in such diverse tectonic settings as intraplate calderas, intraplate continental crust, and volcanic arcs on continental margins. The limited information available suggests that the apparent contrasts in growth styles do not depend principally on tectonic setting. Perhaps the contrasts reflect characteristic differences in magma-reservoir size and depth for rhyolitic versus dacitic systems, and in fluidity for the two magma types.

Using Mount St. Helens and Santiaguito as guides to dacitic systems, domes of composite structural origins (that is, endogenous and exogenous) grow episodically during periods of years to decades. During such growth, the magma of an early-erupted phase can totally solidify before the following volume of dome-forming magma appears at the surface. To the late-extruded batch of melt, the early solid dome rock may simply be additional crust to traverse, in which case growth is necessarily exogenous. However, a sequence of phases of endogenous growth to produce a dacitic dome presumably could maintain a liquid dome core if interphase intervals were brief relative to cooling and solidification times associated with each pulse of magma extrusion.

Using the Taylor Creek Rhyolite as a guide to the formation of a rhyolite dome, growth occurs during a continuous event so brief that a viscous liquid core is always present; the liquid effectively buffers a dome in favor of endogenous growth. This style of growth may reflect the presence of a relatively voluminous, upper-crustal magma reservoir, which favors a process of continuous dome formation, in contrast to a smaller, deeper, though perhaps frequently replenished (from greater depth) reservoir that sporadically feeds a dacitic dome. Differing characteristic viscosities for contrasting compositional and structural dome types also may play a role. A relatively lower barrier to flow associated with the viscosity of dacitic magma might favor frequent repeated tapping of a crustal reservoir in contrast to a single tap from a more viscous system.

Different types of theoretical models have been developed to describe the process of lava-dome growth. One assumes that dome-forming magma is a Newtonian fluid of constant viscosity (Huppert and others, 1982) throughout the period of dome formation; another assumes a Newtonian fluid of constant viscosity enveloped in a solid brittle container of finite tensile strength (Iverson, 1990); and a third assumes a viscoplastic fluid of constant yield strength and viscosity (Blake, 1990). We suggest that each of these models has limited application to dome formation as evidenced by the well-documented history of growth for some historic examples and by the internal structures of some older domes.

Lessons learned at Mount St. Helens and Santiaguito make it unlikely for any model based on a constant-viscosity fluid, with or without a yield strength or brittle shell, to accurately describe the formation of such a dome. Individual episodes of dome growth may be amenable to accurate theoretical analysis, but the cross-sectional structure and outer form of the eventual composite geologic body will not likely bear much resemblance to a theoretically defined counterpart. Even individual episodes of growth may be difficult or impossible to model theoretically, especially after initial episodes have built an edifice, because theory usually describes the spreading of a viscous fluid over a level or only gently inclined surface.

In contrast, we believe that purely endogenous domes are far more amenable to theoretical analysis. With reference to the Taylor Creek Rhyolite, growth of an eruptive unit apparently involved the continuous presence of a viscous liquid core, although viscosity likely varied with time and position in a growing dome. The formation of a thickening shell of flow-generated breccia might be viewed as analogous to a brittle shell (Iverson, 1990), but whether or not such a shell had tensile strength is debatable. Field evidence indicates that breccia forming on the top and lateral margins of a growing Taylor Creek Rhyolite dome was an unconsolidated mass of tumbled blocks, a deposit that is unlikely to have tensile strength. Basal breccia may have had tensile strength during dome growth, as a result of partial welding caused by the load and heat of overlying melt, but dome growth does not occur at or through the base. We view the structural effect of flow breccia as two-fold, varying with position on a growing dome. At the top, breccia probably is a load with no tensile strength, carried passively on a flowing molten core. At the lateral margins, breccia accumulates and can eventually form a thick wedge, again probably with no tensile strength, whose buttressing effect can induce an upward component of flow in an otherwise laterally spreading viscous body. This simple scenario can become complicated if the surface over which growth occurs is steep and uneven or if the volumetric rate of eruption fluctuates greatly. Such complications apparently were rare or absent during the formation of Taylor Creek Rhyolite domes. Yet even for this relatively uncomplicated situation, an accurate theoretical description of dome growth must account for the facts that (1) viscosity of the molten core varies in space and time, and (2) a transition from viscous fluid to brittle solid produces breccia that changes boundary conditions of the growing dome. In conjunction with possible disruption of continuity in time and rate of magma extrusion, these time and space changes in magma flow over the ground surface are key factors in producing the final structure and shape of a dome.

REFERENCES CITED

Blake, S., 1990, Viscoplastic models of lava domes; *in* Fink, J.H., ed., Lava flows and domes: Springer-Verlag, p. 88–126.

Cather, S.M., 1990, Stress and volcanism in the northern Mogollon-Datil volcanic field, New Mexico: Effects of the post-Laramide tectonic transition: Geological Society of America Bulletin, v. 102, p. 1447–1458.

Champion, D.E., Duffield, W.A., and Dalrymple, G.B., 1991, $^{40}Ar/^{39}Ar$ ages and paleomagnetic secular variation tightly constrain the life span of a dome field: Eos Transactions, American Geophysical Union, v. 72, no. 44, p. 138.

Christiansen, E.H., Sheridan, M.F., and Burt, D.M., 1986, The geology and geochemistry of Cenozoic topaz rhyolites from the western United States: Geological Society of America Special Paper 205, 82 p.

Christiansen, R.L., and Lipman, P.W., 1966, Emplacement and thermal history of a rhyolite lava flow near Fortymile Canyon, southern Nevada: Geological Society of America Bulletin, v. 77, p. 671–684.

Delaney, P.T., and Pollard, D.D., 1981, Deformation of hostrocks and flow of magma during growth of minette dikes and breccia-bearing intrusions near Ship Rock, New Mexico: U.S. Geological Survey Professional Paper 1202, 61 p.

Duffield, W.A., 1990, Eruptive fountains of silicic magma and their possible effects on the tin content of fountain-fed lavas, Taylor Creek Rhyolite, New Mexico; *in* Stein, H.J., and Hannah, J.L., eds., Ore-bearing granite systems: Petrogenesis and mineralizing processes: Geological Society of America Special Paper 246, p. 251–261.

Duffield, W.A., and Dalrymple, G.B., 1990, The Taylor Creek Rhyolite of New Mexico: A rapidly emplaced field of lava domes and flows: Bulletin of Volcanology, v. 52, p. 475–487.

Duffield, W.A., and du Bray, E.A., 1990, Temperature, size, and depth of the magma reservoir for the Taylor Creek Rhyolite, New Mexico: American Mineralogist, v. 75, p. 1059–1070.

Duffield, W.A., Reed, B.L., and Richter, D.H., 1990, Origin of rhyolite-hosted tin mineralization: Evidence from the Taylor Creek Rhyolite, New Mexico: Economic Geology Bulletin, v. 85, p. 392–398.

Duffield, W.A., Richter, D.H., and Priest, S.S., 1987, Preliminary geologic map of the Taylor Creek Rhyolite, Catron and Sierra Counties, New Mexico: U.S. Geological Survey Open-File Report 87–515, scale 1:50,000.

Duffield, W.A., and Ruiz, J., 1992a, Compositional gradients in large reservoirs of silicic magma as evidenced by ignimbrites versus Taylor Creek Rhyolite lava domes: Contributions to Mineralogy and Petrology, v. 110, p. 192–210.

Duffield, W.A., and Ruiz, J., 1992b, Evidence for the reversal of gradients in the uppermost parts of silicic magma reservoirs: Geology, v. 20, p. 1115–1118.

Eggleston, T.L., 1987, The Taylor Creek district, New Mexico: Geology, petrology, and tin deposits: Socorro, New Mexico Institute of Mining and Technology, PhD. thesis, 473 p.

Fink, J.H., 1983, Structure and emplacement of a rhyolite obsidian flow: Little Glass Mountain, Medicine Lake Highland, northern California: Geological Society of America Bulletin, v. 94, p. 362–380.

———1984, Structural geologic constraints on the rheology of rhyolite obsidian: Journal of Non-Crystalline Solids, v. 67, p. 135–146.

———1987, ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, 145 p.

———1990, ed., Lava flows and domes: Springer-Verlag, 249 pp.

Fink, J.H., and Manley, C.R., 1987, Origin of pumiceous and glassy textures in rhyolite flows and domes; *in* Fink, J.H., ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 77–88.

Fries, C., Jr., 1940, Tin deposits of the Black Range, Catron and Sierra Counties, New Mexico: A preliminary report: U.S. Geological Survey Bulletin 922–M, p. 355-370.

Huppert, H.E., Shepard, J.B., Sigurdsson, H., and Sparks, R.S.J., 1982, On lava dome growth, with application to the 1979 lava extrusion of the Soufrière of St. Vincent: Journal of Volcanology and Geothermal Research, v. 14, p. 199–222.

Iverson, R.M., 1990, Lava domes modeled as brittle shells that enclose pressurized magma, with application to Mount St, Helens; *in* Fink, J.H., ed., Lava flows and domes: Springer-Verlag, p. 47–69.

Lawrence, V.A., 1985, A study of the Indian Peaks tin-bearing rhyolite dome-flow complex, northern Black Range, New Mexico: Boulder, University of Colorado, MS thesis, 112 pp.

Lawrence, V.A., and Richter, D.H., 1986, Geologic map of the Indian Peaks West quadrangle, Catron County, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF–1849, scale 1:24,000.

Manley, C.R., 1989, Cooling, devitrification, and flow of large hot rhyolite lava flows: Numerical modeling results: New Mexico Bureau of Mines and Mineral Resources Bulletin 131, p. 174.

Manley, C.R., and Fink, J.H., 1987, Internal textures of rhyolite flows as revealed by research drilling: Geology, v. 15, p. 549–552.

McIntosh, W.C., Sutter, J.F., Chapin, C.E., and Kedzie, L.L., 1990, High-precision $^{40}Ar/^{39}Ar$ sanidine geochronology of ignimbrites in the Mogollon-Datil volcanic field, southwestern New Mexico: Bulletin of Volcanology, v. 52, p. 584–601.

McIntosh, W.C., Sutter, J.F., Chapin, C.E., Osburn, G.R., and Ratté, J.C., 1986, A stratigraphic framework for the eastern Mogollon-Datil volcanic field based on paleomagnetism and high-precision $^{40}Ar/^{39}Ar$ dating of ignimbrites—a progress report: New Mexico Geological Society Guidebook 37, p. 183–195.

Ratté, J.C., Marvin, R.F., Naeser, C.W., and Bikerman, M., 1984, Calderas and ash flow tuffs of the Mogollon Mountains, southwestern New Mexico: Journal of Geophysical Research, v. 89, p. 8713–8732.

Richter, D.H., 1978, Geologic map of the Spring Canyon quadrangle, Catron County, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF–966, scale 1:24,000.

Richter, D.H., Eggleston, T.L., and Duffield, W.A., 1986a, Geologic map of the Wall Lake quadrangle, Catron County, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF–1909, scale 1:24,000.

Richter, D. H., Lawrence, V. A., and Duffield, W. A., 1986b, Geologic map of the Indian Peaks East quadrangle, Catron County, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF–1850, scale 1:24,000.

Rose, W.I., 1987, Volcanic activity at Santiaguito Volcano, 1976-1984; *in* Fink, J.H., ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 17–27.

Rye, R.O., Lufkin, J.L., and Wasserman, M.D., 1990, Genesis of rhyolite-hosted tin occurrences in the Black Range, New Mexico, as indicated by stable isotope studies; *in* Stein, H.J., and Hannah, J.L., eds., Ore-bearing granite systems; Petrogenesis and mineralizing processes: Geological Society of America Special Paper 246, p. 233–250.

Swanson, D.A., and Holcomb, R.T., 1990, Regularities in growth of the Mount St. Helens dacite dome, 1980–1986; *in* Fink, J.H., ed., Lava flows and domes: Springer-Verlag, p. 3–24.

Webster, J.D., and Duffield, W.A., 1991, Volatiles and lithophile elements in Taylor Creek Rhyolite: Constraints from glass inclusion analysis: American Mineralogist, v. 76, p. 1628–1645.

Williams, H., 1932, The history and character of volcanic domes: University of California Publications in the Geological Sciences, Bulletin 21, p. 51–146.

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