Structure and emplacement of a rhyolitic obsidian flow:  
Little Glass Mountain, Medicine Lake Highland, northern California

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ABSTRACT

Many rhyolitic obsidian flows show consistent stratigraphic relations among textual units exposed in the flow fronts of undissected flows and in cross sections of older flows. The stratigraphy of the Holocene Little Glass Mountain rhyolitic obsidian flow consists of (from bottom to top): air-fall tephra deposits, basal breccia, coarsely vesicular pumice, obsidian, finely vesicular pumice, and surface breccia. Slightly crystalline rhyolite occurs near the vent areas. A model of obsidian-flow emplacement based on these textual relations is presented. This stratigraphy may reflect the distribution of volatiles within the magma source region, with the interlayered contact between coarsely vesicular pumice and overlying obsidian indicating stratification of volatiles in the magma body.

The distribution of pumiceous and glassy zones along with the orientations of flow banding can be used to map the surface structure of rhyolitic obsidian flows. This complex structure, as mapped on the Little Glass Mountain flow, reflects both the initial flow stratigraphy and subsequent deformational processes. During emplacement of the lava, three processes disrupt the initial flow configuration: the rise of coarse pumice diapsis from the base of the flow, the inward propagation of fractures in areas of extension, and surface folding in sites of flow-parallel compression. Subvertical flow banding in vent areas indicates that fracturing accompanies the emergence of lava; most of the observed upper surface of a dome originates as a fracture plane. The structure of domes that form over vent areas may reflect the orientation of dike-like conduits as well as the local state of stress during extrusion.

INTRODUCTION

The surface structure of basaltic lava flows has been the subject of numerous studies that relate morphology to flow processes and lava rheology (Wentworth and MacDonald, 1953; Peck, 1966; Swanson, 1973; Fink and Fletcher, 1978; Peterson and Tilling, 1980). Comparable work on rhyolite flows has been hindered by a lack of observations of active flows and by the seemingly random distribution of blocks on the surfaces of young, undissected flows. However, close examination of Little Glass Mountain, a Holocene rhyolitic obsidian flow in northern California, shows the surface to be composed of four principal textual units; these vary in color, specific gravity, and degree of vesiculation. Mapping the distribution of these units reveals that the surface structure results from three deformational processes: compression during advance of the lava, fracturing due to cooling and radial expansion of the flow, and diapirism caused by the presence of a light pumiceous base beneath the non-vesicular core of the flow. Interactions among these three processes lead to the complex surface patterns observed on Little Glass Mountain and other rhyolite flows.

In this paper, the textual units and their distribution will first be described and interpreted, using an emplacement model for rhyolitic obsidian flows. Maps and photographs of the surface structure will then be explained by a deformational model that takes account of the mechanical properties of the different textual units. Finally, the structure of domes will be used to interpret local and tectonic stress patterns at the time of extrusion.

Geologic Setting

Little Glass Mountain lies on the southwest flank of the Medicine Lake Highland shield volcano in northern California, near the southern end of the Cascade vol-

Figure 1. Map showing location of Medicine Lake Highland Volcano and the major Cascade volcanoes. Heavy line indicates outline of volcano. Dotted line shows margin of caldera. Dashed lines represent prominent faults. BGM = Big Glass Mountain Flow; LGM = Little Glass Mountain Flow; ML = Medicine Lake.

Figure 2. U.S. Forest Service photograph of Little Glass Mountain, showing locations of Figures 20 through 23. Light color of surrounding area is due to presence of tephra. Scale bar = 500 m. North is to top.

A Model for Obsidian Flow Emplacement

Consider the emplacement of a low volume (less than 1 km³) of relatively dry (less than 1.0% volatiles by weight) rhyolitic magma. As this body approaches the surface, volatiles exsolve and rise to its top. Lower confining pressure leads to frothing of the volatile-rich cap as the stratified mass works its way upward (Fig. 3a). Contact with ground water also contributes to the formation of a gas-rich carapace. This vesiculation may generate one or more explosive eruptions of tephra (Fig. 3b). The remaining volatile-rich magma reaches the surface as a highly inflated pumiceous lava (Fig. 3c). The transition from discrete pumice particles to a continuous lava flow occurs when gas pressure in the vesicles is no longer sufficient to overcome the tensile strength of the magma. Once extruded, the lava flows due to the relatively low viscosity of the glassy septa between vesicles; such motion causes the bubbles to be flattened and distorted.

As the eruption continues, bubble-free obsidian flows out over the earlier emplaced coarsely vesicular pumice, compressing and shearing the latter into a basal layer of irregular thickness (Fig. 3d). This lava is slightly less viscous but more dense than the coarse pumice. The transition from coarse pumice to obsidian is gradual, so that some vesicular material continues to be extruded with the obsidian, forming blebs of different sizes, which are stretched into layers parallel to the flow direction.

As the obsidian rides over the coarse pumice, some volatiles continue to evolve from the cooling upper flow surface, forming a finely vesicular carapace that then insulates the flow interior (Fig. 3e). Bubbles in this layer are smaller and less distorted than those in the lower pumice unit, due to the lower temperature, higher viscosity, and lower shear stresses at the flow surface. Most contacts between obsidian and finely vesicular pumice are gradational, although early-formed masses of fine pumice may break off in zones of high strain and become stretched parallel to the obsidian, locally giving interlayered contacts.

Magma remaining in the conduit has more time to crystallize. The final material to erupt piles up over the vent rather than advancing outward, due to its higher crystal content and viscosity and lower temperature (Fig. 3f). Eventually, lava plugs the vent. New cracks then open in the dome, through which additional lava extrudes; an
Figure 3. Diagram showing emplacement of small rhyolite lava flow with concurrent development of flow stratigraphy. Geometry of rising magma in a and b is highly schematic.

explosive “throat-clearing” leads to a new tephra layer; or magma may move laterally and erupts at a nearby center, a process that may form a chain of coalescing domes and flows.

This model implies that flow stratigraphy should consist of a basal layer or layers of tephra, overlain by coarsely vesicular pumice, obsidian, and finely vesicular pumice. Toward the end of the eruptive cycle, crystalline rhyolite forms a summit dome, and if the flow cools slowly enough, crystallization occurs in the flow interior. Consequently, rhyolite appears as domes over the vent areas, with finely vesicular pumice on the upper flow surface. Obsidian forms the core, and coarsely vesicular pumice is found at the distal margins and at the base of the flow. Movement and cooling of the lava causes the upper surface to fracture into blocks that cascade off the flow front and become buried by advance of the lava; hence the stratigraphy also includes basal and surface layers of breccia. Repetition of any of these stages during an eruption will cause variations in the above stratigraphy.

Figure 4. Coarsely vesicular pumice unit. (a) Hand specimen. (b) Thin section (25× enlargement).

STRATIGRAPHY OF LITTLE GLASS MOUNTAIN

It may seem unusual to discuss the “stratigraphy” of a single lava flow. However, the textures found on Little Glass Mountain and other flows occur in discrete layers with consistent spatial relations. This sequence is most easily understood in terms of a stratigraphic arrangement.

In aerial photographs of Little Glass Mountain, the surrounding forests appear to have a white soil. This is actually an airfall pumice deposit that underlies the lava flow. The rhyolitic pumice consists of poorly sorted gray lapilli in a coarse gray ash (Heiken, 1978). Isopach maps indicate that the pumice erupted from a vent or vents now buried by Little Glass Mountain. The volume of this tephra constitutes about 9% of the volume of the subsequent lava flows. No tephra was found on the surface or interlayered in the flow fronts of Little Glass Mountain, indicating that explosive activity ceased upon extrusion of lava. Vesicles seen in photomicrographs of the tephra are elongated and parallel to each other. Pumice lapilli have fracture surfaces oriented perpendicular to the direction of vesicle elongation, suggesting that fragmentation occurred through the stretching and pulling apart of the vesicular magma in the vent (Heiken, 1978).

Contacts between the tephra and the overlying lava-flow units are concealed by talus in most of the flow fronts. The unit that most commonly occurs directly over the talus is a coarsely vesicular, brownish to greenish-gray pumice. In cross sections of other flows that show similar stratigraphy,
such as the Banco Bonito Flow in the Valles Caldera of New Mexico and the Roches Rossa Flow in Lipari, Italy, coarse pumice passes downward into a brecciated zone that overlies the basal tephra, with no intervening soil horizons.

The coarsely vesicular pumice (Fig. 4a) has the lowest bulk density of any of the textural types (sp. gr. = 0.8 to 2.0 g/cm³) and is consequently mined preferentially in the quarries found on many rhyolitic obsidian flows (Chesterman, 1956). Vesicles, which generally make up more than 50% by volume of this pumice, are ovoid to highly elongate and range from less than one millimetre to a few centimetres in diameter, with the most distorted bubbles developing a highly filamentous appearance. Vesicles seen in thin section are commonly flattened and folded, giving the pumice a close resemblance to the tephra (Fig. 4b).

Coarse pumice grades upward across a zone less than a few metres wide into a prominent black obsidian unit that is largely free of vesicles and phenocrysts (Fig. 5). The lava ranges from homogeneous coarse pumice, to pumice with scattered glassy blebs and layers, to an equal mixture of pumice and obsidian, to obsidian with pumiceous inclusions, and finally to pure obsidian. Within the pumice, some round glassy inclusions have elongated tails, and some glassy layers widen locally into nearly circular structures, illustrating a transition from isolated blebs to continuous layers (Fig. 6).

Ubiquitous layering within the obsidian, ranging from tens of microns to several centimetres in thickness, results primarily from varying concentrations of feldspar crystalites. The needle-like crystals are generally aligned parallel to each other within a layer, although they need not be parallel to the boundaries of the layer. Layers may extend continuously for several metres or may be disrupted by small faults of a few centimetres displacement. These layers, as well as the interlayered contact zone between the obsidian and coarse pumice, may be concentrically or isoclinaly folded.

Obsidian outcrops in flow fronts are usually between 2 and 15 m thick. They grade upward into a finely vesicular pumice unit that forms a carapace over much of the flow surface. This fine pumice differs from the obsidian only in its higher concentration of vesicles, which may be as much as 30%. Bubble shapes range from spherical in samples that have less than about 25% vesicles by volume to elongate in more vesicular samples; vesicles are rarely as distorted as those in the coarsely vesicular pumice. Bubble size is commonly less than one millimetre in diameter, but ranges up to a centimetre in some places. Like the obsidian, this unit exhibits banding defined by crystalite concentrations, but it also contains layers defined by bubbles.

Contacts between this pumice and the obsidian are of two types: interlayered and gradational. Interlayered contacts parallel foliations as in the coarse pumice–obsidian contacts. Inclusions of finely vesicular pumice are stretched into layers up to 20 cm thick. Gradational contacts are typically seen in vertically foliated outcrops where obsidian near the base becomes increasingly bubble-charged upward. The color of the outcrop passes upward from black to gray to white as the bubble concentration increases. Figure 7b illustrates this gradation microscopically for the outcrop shown in Figure 7a.

Contacts between the coarse and fine pumice are rare because these units are generally separated by a zone of obsidian. In some places, blocks of fine pumice perch unconformably on outcrops of coarse pumice (Fig. 8). These erratic blocks may rest a few metres above the mean flow surface without any nearby fine pumice outcrops of comparable height. Similarly, isolated blocks or extensive bands of fine pumice may lie in the middle of a large expanse of coarse pumice without an obvious source. Both of these relationships apparently represent stratigraphic anomalies caused by deformation of the flow surface during or after its emplacement (Fink, 1980a).

The sequence described above (tephra overlain by coarse pumice, obsidian, and fine pumice) is observed in the flow fronts and over much of the surface of Little Glass Mountain and other rhyolitic obsidian flows in the Medicine Lake Highland and elsewhere. Near the vent areas, however, another unit predominates, which resembles the fine pumice. This rock is a uniform gray to dark bluish-gray rhyolitic glass with numerous gabbro xenoliths and widely scattered pyroxene and feldspar phenocrysts. It is thoroughly banded and has a specific gravity of 2.1 to 2.3. Foliations are defined by feldspar microlites, which are suspended in a glassy matrix. The unit differs from the obsidian and fine pumice primarily in its distinctive waxy luster, its higher concentration of crystalites, and its strong tendency to develop deep smooth fractures that cut across foliations. The
rhyolite unit has only limited contacts with the other three lava textures. It contains a finely vesicular surface crust as much as 1 m thick that grades downward into bubble-free rhyolite. Coarsely vesicular pumice outcrops interrupt continuous foliations in the rhyolite, especially where exposed in valley-like cracks as much as 10 m deep (Fig. 9). Blocks of rhyolite perch unconformably on top of areas of fine pumice and obsidian, but these contacts are difficult to identify due to local similarities between fine pumice and rhyolite.

**Distribution of Textures**

The general distribution of lava textures on Little Glass Mountain is typical of many rhyolitic obsidian flows. Mapped exposures in flow fronts show a relatively uniform thickness of obsidian wrapping around the flow, overlain by finely vesicular pumice and underlain by coarsely vesicular pumice. The coarse pumice layer has a more variable thickness than the obsidian; this variation reflects both differences in the thickness of the original deposit and the irregular height of the concealing talus apron. Figure 10a shows the southern flow front of the northemmost (Inyo) obsidian dome on Glass Creek, north of Long Valley Caldera, California (Wood, 1977). A prominent black obsidian layer can be seen below the white surface layer of finely vesicular pumice. A second, lower layer of coarsely vesicular pumice is visible toward the right-hand side of the photo; measured thicknesses for a portion of this outcrop are shown in Figure 10b.

Much of the upper flow surface is covered by finely vesicular pumice, with outcrops of coarsely vesicular pumice concentrated toward the flow fronts. Obsidian outcrops are relatively restricted and occur sandwiched between the upper-flow surface and the flow front. Outcrops of rhyolite are restricted to the central vent areas, which commonly are dome shaped with steeper slopes than the rest of the flow surface. Scattered outcrops of coarsely vesicular

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**Figure 7a.** Gradational contact between obsidian and finely vesicular pumice units.

**Figure 7b.** Thin sections of samples taken from different positions within gradational contact, showing progressively greater disruption of obsidian foliation by bubbles in finely vesicular pumice (25× enlargement).
Figure 8. Unconformable "erratic" block of finely vesicular pumice unit resting on large outcrop of coarsely vesicular pumice.

Figure 9. An 8-m-deep fracture in rhyolite unit intruded by an ~2-m-high outcrop of coarsely vesicular pumice.

Figure 10. (top) Southern flow front of northernmost Glass Creek (Inyo) obsidian dome, eastern California. (bottom) Tape and compass map of portion of flow front of Glass Creek dome.
pumice occur at the base of rifts up to 10 m deep in the rhyolite.

Implications of Rhyolite Stratigraphy

The stratigraphic arrangement of Little Glass Mountain can be observed in other Holocene rhyolitic obsidian flows, including Big Glass Mountain and the Crater Glass Flows in the Medicine Lake High-land, Big Obsidian Flow in Newberry Volcano, Oregon, and the Roche Rossa Flow on the island of Lipari, Italy. Each of these flows has well-preserved surfaces where textural relations can be discerned. On Roche Rossa, outcrops are covered by an orange-colored lichen that obscures the original textures, but when fresh surfaces are exposed, the same relationships as those on Little Glass Mountain are observed.

In order to see obsidian-flow cross sections, one must examine flows old enough to have been dissected, yet young enough to have their glass preserved. The 100,000-yr-old Banco Bonito Flow in the Valles Caldera, New Mexico, has been deeply dissected along one margin by San Antonio Creek. Here one may locally observe 1 to 2 m of basal breccia overlain by a similar thickness of coarse pumice and as much as 10 m of obsidian. Most of the flow is horizontally banded, although large pods of glassy obsidian show prominent vertical flow structure. Near the top of the cliff face, the foliation becomes predominantly vertical, which may correspond to the finely vesicular surface of Little Glass Mountain. Not much structure is preserved on the surface of this flow. Other Holocene flows, such as Sugarloaf Mountain in the Coso Volcanic field (100,000 yr old; Bacon and others, 1980), have very few exposed cross sections or surface outcrops. Nonetheless, scattered road cuts allow distinction of three textural types that may correspond to obsidian and coarse and fine pumice. Older flows, such as the Tertiary Andy's Dome (Moyer, 1982) in northwestern Arizona, also contain good cross sections with stratigraphic information still discernible (Fig. 11). This 50-m-thick dome and flow complex is cut through by Burro Creek, which reveals an obsidian core overlying 2 to 3 m of basal breccia but lacking a coarsely vesicular pumice zone. The upper few metres of the flow have upturned foliations and lighter color than the horizontally banded central and basal portions.

The close association between these small-volume extrusions and tephra eruptions may be a genetic one. Eichelberger and Westrich (1981) have suggested that the water content of obsidian fragments in tephra deposits reflects the volatile content of the magma body. In the present model, eruptions of tephra and lava are considered to be continuous, with the transition occurring when tensile stresses associated with the rise of magma fall below the effective tensile strength of the vesicular magma. Subsequent lava is volatile-depleted and more glassy; postemplacement vesiculation forms the carapace of finely vesicular pumice. The thin interlayered contact zone between coarsely vesicular pumice and obsidian implies a discrete zonation of the parent magma body. Furthermore, the presence of groups of domes and flows of similar age and textural makeup in the Medicine Lake High-land (Heiken, 1978), near South Sister Volcano (Williams, 1944), in Long Valley Caldera (Bailey and others, 1976), Inyo Craters (Wood, 1977), the Coso Volcanic field (Bacon and others, 1980, 1981), Newberry Volcano (MacLeod and others, 1981), and elsewhere suggests that each group of extrusions taps a larger body of magma that is capable of regenerating its stratification by continued exsolution of volatiles after each eruption.

The stratigraphy of Little Glass Mountain is not typical of all rhyolite flows but is most common among relatively dry flows of low volume. Instead of the asymmetric vertical zonation seen in Little Glass Mountain, most larger flows show concentric layers overlying and underlying a crystalline core: glassy, spherulitic, pumiceous, and brecciated zones (Christiansen and Lipman,

Figure 11. Cross section of rhyolitic Tertiary Andy's Dome, exposed by Burro Creek near Kaiser Spring area of northwestern Arizona. Light-colored tuff cone underlies darker obsidian flow. Wedge of basal breccia visible on left side of photo. Foliations in feeder dike (center) cut through tuff cone and are continuous with those in the overlying lava flow. Foliations in flow are primarily horizontal except for upper 3 to 5 m where they are vertical. Cross section shown is ~1.5 km long and 50 to 75 m high.
There are at least two possible explanations for the aphyric cores of obsidian flows. Dry magma has high viscosity, which prevents or retards the diffusion of ions necessary for crystal growth. Alternatively, the glassiness may reflect very rapid emplacement. The volatile-rich cap of one of these magma bodies, inferred from the stratigraphy, may force its way to the surface, clearing a pathway that allows the rhyolitic magma to be rapidly extruded. Observations of the emplacement of several dacite domes at Mount St. Helens from 1980 to 1982 have shown that moderate volumes of viscous lava may reach the surface quite rapidly. Rhyolite lacking tephra precursors might have taken longer for its ascent, allowing crystallization to have proceeded further.

The observed structure and morphology of rhyolitic obsidian flows reflect both the original distribution of textures, described above, and the subsequent deformation that accompanies emplacement. In the next sections, I will consider the deformational consequences of this stratigraphy and provide interpretations of mapped portions of the upper surface of Little Glass Mountain and other rhyolitic obsidian flows. Finally, the structure and arrangement of domes will be used to interpret local and tectonic stress patterns.

DEFORMATION AND SURFACE STRUCTURE

Rheology of Obsidian and Pumice

The textural relations described above define the initial configuration of the lava flow. The final structural arrangement observed in the field results from several deformational processes. Before discussing the development of these final structures, it is useful to consider briefly the rheological behavior of the lava on the basis of field evidence and laboratory measurements cited in the literature. For a more thorough review of lava rheology, the reader is referred to the various papers of Shaw (1963, 1965, 1969), Shaw and others (1968), Hulme (1974), or Peterson and Tilling (1980).

The rheological behavior of obsidian and pumice depends largely on the temperature and strain rate ($\dot{\epsilon}$) being considered. At temperatures above the liquidus, rhyolite behaves as a Newtonian viscous fluid, with the viscosity ($\eta$) increasing as either the temperature or water content decreases (Shaw, 1963; Friedman and others, 1963; Taniguchi, 1981). At subliquidus temperatures, the rheology becomes more complicated as crystals and bubbles begin to appear. Various simplified models have been used to describe this behavior; one of the most useful is the Bingham model. Bingham materials have a yield strength ($\tau$) that is a quantity of stress that must be exceeded before the lava can begin to deform. Like viscosity, yield strength decreases with increasing water content or temperature or silica content (Muras and McBirney, 1963). At higher stresses, Bingham materials behave like viscous fluids. At low temperatures or stress levels, rhyolitic obsidian and pumice behave as elastic materials (Sakuma, 1951). Under certain conditions, any lava may respond to an applied stress by brittle fracture rather than deforming as an elastic solid or a viscous fluid (Walker, 1969). When the local tensile stress in a lava exceeds the tensile strength, brittle failure occurs. Slight variations in either strain rate or viscosity can cause fracture and flow to occur nearly simultaneously. Obsidian and pumice layers in Little Glass Mountain have nearly identical chemistry (Eichelberger, 1975), so that chemical differences between them arise primarily from the presence of vesicles in the pumice. With increasing porosity, the bulk density of the pumice decreases while its viscosity increases (Williams and McBirney, 1979, p. 125-126; Sicree, 1933; Shepherd, 1938).

In summary, obsidian and pumice may be considered to have rheological properties that depend on strain rate, temperature, and volatile content. In general, the lava deforms according to a stress-strain rate curve of the type shown in Figure 12. For applied stress ($\sigma$) less than yield strength ($\tau$), that is, $\sigma < \tau$, the lava deforms elastically:

$$\dot{\epsilon} = \frac{\sigma}{E}$$

where $\dot{\epsilon}$ = strain and $E$ = Young's modulus. For applied stress greater than yield strength but much less than tensile strength ($\sigma_t$), that is, $\tau < \sigma < \sigma_t$, the lava flows according to:

$$\dot{\epsilon} = \frac{\sigma - \tau}{\eta}.$$

As the applied stress approaches the tensile strength, strain increases very rapidly until fracture occurs.

Mechanical Implications of Obsidian Flow Stratigraphy

Figure 13a shows a profile through a hypothetical 35-m-thick rhyolitic obsidian flow based on measurements of Little Glass Mountain, Northern Glass Creek (Inyo) Obsidian Dome, Roches Rossa Flow in Lipari, Italy, and the Banco Bonito Flow in the Valles Caldera, New Mexico. The stratigraphic layers, from bottom to top, are: tephra, basal breccia, coarsely vesicular pumice, obsidian, finely vesicular pumice, and surface breccia. The tephra deposits are associated with the eruption of the lava but do not represent a part of the moving flow. On the basis of the preceding discussion of mechanical properties, we can construct profiles of several properties and then, by considering the stresses associated with the movement of a typical viscous lava flow, predict the types of structures that might result from such deformation.

Density Profile and Pumice Diapirs.

Measurements of specific gravity for samples of finely vesicular pumice, obsidian, and coarsely vesicular pumice, cited in Fink (1980a) were used to construct a density profile (Fig. 13b) for the stratigraphy of Figure 13a. We are concerned here with the bulk density of the stratigraphic layers, so that the breccia layers should have lower values than the blocks of which they are composed, due to the presence of interstitial void spaces. Density increases inward from the upper surface to a value of 2.2 g/cm$^3$ for the obsidian but then decreases downward across the interlayered contact zone between obsidian and coarsely vesicular pumice to a value of ~1.5. Compaction

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Figure 12. Hypothetical curve of stress ($\sigma$) versus rate of strain ($\dot{\epsilon}$) for lava possessing yield strength ($\tau$) and tensile strength ($\sigma_t$). Brittle failure occurs when stress reaches tensile strength.
should lead to a slight downward increase of density through the basal breccia and tephra. The density inversion between the obsidian and coarse pumice layers provides the basis for a gravitational instability. Hence, we may expect coarsely vesicular pumice to rise buoyantly through the overlying obsidian and fine pumice. If the rate of ascent is high enough relative to the forward velocity of the lava and the cooling rate, then these diapirs could reach the flow surface. Fink (1980a) has described surface outcrops of coarsely vesicular pumice that were interpreted to be such diapirs. These domes and plunging anticlines cored by coarsely vesicular pumice account for a large fraction of the distal flow surface of Little Glass Mountain and may occur singly or in groups of as many as 30 adjacent domes and anticlines. Individual domes range from about 3 to 10 m in diameter and up to several metres in height. On some flow lobes, these outcrops exhibit a regular spacing which has been related to the gravity instability inherent to the flow stratigraphy (Fink, 1980a).

The two most useful criteria for identifying pumice diapirs are their foliation patterns and stratigraphic setting. Foliations generally define the domal or anticlinal shape of the outcrops (see Fig. 14a), except where obscured by fractures. Most coarse pumice outcrops are surrounded by a band or zone of obsidian a few metres wide, which grades outward into finely vesicular pumice. For example, Figure 14b shows a coarse pumice dome bisected by a fracture. Moving outward from the fracture plane, one encounters an obsidian zone separating coarse pumice from fine pumice. In some locations, coarse pumice domes rise up through the overlying fine pumice crust and lift blocks of the surface unit that remain as perched erratics (Figs. 9 and 14a). Where several adjacent outcrops of coarse pumice are exposed, the bordering obsidian may enclose the entire area (see maps, Figs. 20 and 21a). The pervasive nature of this con-
tect relation reflects the fact that, due to the
stratigraphy, coarsely vesicular pumice must
rise up through both the obsidian and finely
vesicular pumice to reach the flow surface.

In places where coarsely vesicular pumice
crops out near the intersection of the flow
front and the upper flow surface, the struc-
ture is better revealed. Figures 15a and 15b
show a plunging anticline cored by coarsely
vesicular pumice at the distal margin of the
Northwest Lobe of Little Glass Mountain.
Approximately 2 m of obsidian drapes over
the exposed coarse pumice core of the fold.
The orientations of large stretched vesicles
are consistent with movement of this coarse
pumice mass outward and upward from the
flow interior. The subhorizontal layer of
obsidian in the upper limb of the fold is
overlain by finely vesicular pumice, which
forms a small syncline whose axis parallels
the crest of the flow front. Moving up onto
the flow surface, one encounters another
band of obsidian followed by a large anti-
clinal region of coarse pumice (Fig. 16).

Temperature Profile and the Inward
Growth of Fractures. Temperature values
within an obsidian flow can be estimated
only approximately. The surface layer of
finely vesicular pumice insulates the interior
so that the obsidian core should maintain a
uniform temperature close to that of its
eruption temperature over most of the
length of a flow. If we assume that the
ambient temperature is about 25 °C and the
initial ground temperature is about 100 °C
(due to heating by the overlying lava), then
we might expect a temperature profile like
that shown in Figure 13c. The main features
of this model are the steep temperature gra-
dient near the flow surface and a constant
or nearly constant interior temperature.

Obsidian and pumice have a strong ten-
dency to fracture on cooling (see Fig. 9).
Thus thermal contraction during cooling of
the flow surface should lead to inward
propagation of cracks, whenever the ther-
mal stresses exceed the tensile strength of
the lava. The tensile strength of pumice is
not reported in the literature, but using
values for trachyte (Jaeger and Cook, 1976),
we can place an upper bound at 30 to 400
bars. Thermal stresses at the surface of the
flow may be expressed as:

\[
\sigma_\tau = \left(\frac{\alpha E \Delta \theta}{1 - n}\right)
\]

where \(\alpha\) is the linear coefficient of thermal
expansion, \(E\) is Young's modulus, \(\Delta \theta\) is
the temperature drop, and \(n\) is the Poisson's
ratio (Timoshenko and Goodier, 1963).

The elastic properties of vesicular rhyolite
are also unreported in the literature, but
using a range of estimates for obsidian,
welded and unwelded tuffs, and nonvesicu-
lar rhyolite (Clark, 1966), we can approxi-
mate the tensile strength to be:

\[
\sigma_{\tau} = (0.01 \text{ to } 10.0) \left(\Delta \theta \text{ bars, °C}\right).
\]

Taking minimum values for the elastic
parameters, we find that a temperature drop
of a few hundred degrees is sufficient to
cause the surface to fracture. Such cracks
propagate inward until they reach a level
where the stress drop due to cooling is less
than the tensile strength of the lava.

On Little Glass Mountain, fractures pene-
trate to a maximum depth of about 8 m,
which corresponds to the thickness of the
finely vesicular pumice layer measured in
flow fronts. Radial expansion of a flow
results in additional, circumferential stresses
near the margin. These stresses will thus
cause the orientation of some fractures to be
perpendicular to flow fronts, although their
initiation may be caused by thermal con-
traction.

In addition to cooling and spreading of
the flow, a third source of fracture is the rise
of coarsely vesicular pumice diapirs to the
flow surface. As a diapir of coarse pumice
approaches the surface, it creates tensile
stresses in the overlying crust. The rising
diapir becomes split by a downward propa-
gating fracture with the halves migrating
laterally (Fig. 17). When two or more paral-
lel coarse pumice diapirs are spreading in
this manner, lava in the zone between the
two fractures may become compressed and
uplifted. Figure 18a shows a 4-m-high out-
crop of fine pumice crust sandwiched
between two coarse pumice diapirs. Figure
18b shows foliations, and Figure 18c is an
interpretation of the structure. The dis-
tances separating the opposing walls of a
fracture increase from zero near the base to
as much as 10 m at the coarse pumice-
obsidian contacts. Fractures may cut
through a series of coarse pumice anticlines,
forming a continuous valley several metres
deep and tens of metres long. These valleys
commonly trend perpendicular to the flow
front (Fig. 19), with their opposing surfaces
showing foliation patterns that are mirror
images of one another. These walls are
smooth, rounded, and outwardly convex.

Viscosity Profile and Surface Folding.

Figure 15. Overturned anticline of coarse pumice exposed in front of Northwest Lobe, Little Glass Mountain. (a) Obsidian outcrop wraps around coarse pumice core of fold, which dips about 30° into flow. (b) View to south of same fold. Large vesicles stretched by outward flow of coarse pumice.
The viscosity profile (Fig. 13d) reflects both the density and temperature profiles described above. Here again we estimate only the approximate shape of the curve. The viscosity of the obsidian core will depend upon the temperature and water content. Viscosity of the coarse pumice will be modified by variations in both temperature and porosity. Decreasing temperatures and lower density toward the base of the flow tend to increase viscosity.

As the flow advances, it will be subjected to compression and extension due to changes in topography and flow-lobe configurations. The rapid decrease in viscosity associated with the steep surface-temperature gradient may lead to a surface-folding instability at sites of compression (Fink and Fletcher, 1978; Fink, 1980b), resulting in surface folds or ridges oriented transverse to the flow. Regular spacings of these ridges may be correlated to the steepness of the viscosity profile and hence to the thickness of the stiff, nearly congealed crust of the flow. The steeper the gradient, the thicker the crust and the wider the spacing of ridges (Fink and Fletcher, 1978).

Surface folds can be recognized by both detailed foliation patterns (flow banding) measured in the field and by the continuity of topographic ridges (Fig. 20). Based solely on the stratigraphy, surface folds should be found exclusively in the finely vesicular pumice crust. Although such folds do occur, the original subvertical foliation patterns in the fine pumice make them difficult to identify. More commonly these folds stretch across the flow surface as parallel ridges that cut contacts between the different textural units, as seen in aerial photographs (Fig. 2) and on maps (Figs. 20 and 21). The synclinal portions of these folds are rarely defined by foliations; more commonly they are identified as continuous bands of finely vesicular pumice lying in troughs parallel to and in between the more prominent anticlinal ridges (Figs. 14a and 20). The spacing of surface folds ranges up to several tens of metres on rhyolitic obsidian flows.

**Combinations of Diapirism, Folding, and Fracturing**

Most deformation of obsidian-flow surfaces occurs near the flow fronts where low-density pumice is concentrated and both tensile and compressive stresses are highest. Here we consider maps of two distal portions of Little Glass Mountain that have had relatively little deformation, so that much of the flow surface is composed of light-colored, finely vesicular pumice (Fig. 20). Discontinuous outcrops of darker coarse pumice and obsidian become more extensive adjacent to the flow front. Some of these coarse pumice outcrops are split by 1- to 2-m-deep fractures with the halves having spread laterally by as much as 20 m. These fractured areas are topographically lower than the surrounding fine pumice. Surface folds may be delineated by anticlinal and synclinal foliation patterns within the coarse pumice and obsidian, and as topographic ridges and troughs within the fine pumice. Fold wavelengths are between 8 and 15 m, and amplitudes range from 1 m within the center of the coarse pumice out-
crops to 3 m near the flow front. Continuous ridges are not well developed. This portion of the flow was apparently undergoing north-south extension and east-west, flow-parallel compression as the lava advanced slowly across a gentle slope. The predominance of ridges over fractures in this area suggests that expansion of the flow was restricted by topography or by a decrease in lava supply.

The part of the Northwest Lobe mapped in Figures 21 and 22 has undergone more extensive diapirism and extension than that in Figure 20. The shapes of coarse pumice outcrops vary from subcircular near the vent to elongate near the flow front, and spacings between outcrops show a corresponding decrease from about 70 m to 20 m near the flow front. The area mapped in Figure 21a consists of several coalesced coarse pumice domes that have been folded and fractured. Spreading across fractures was extensive. As shown in cross section N–S (Fig. 21b), separation of opposing fracture surfaces is as much as 50 m on individual fractures and more than 100 m total. Obsidian that was originally positioned over the coarse pumice was broken and pushed apart by the rising diapirs. Between parallel fractures, this obsidian became compressed into tight synclines (Fig. 21b; compare with Figs. 17 and 18).

On the basis of underlying topography, it appears that the flow direction was mainly to the west, although a small volume of lava moved northward at a late stage of advance. This final movement might have been associated with spreading and lowering of the flow surface by 1 to 3 m. The extensive exposure of coarse pumice in this area illustrates a type of stratigraphic inversion resulting from gravity instability that is common in the distal portions of these flows (compare with Fig. 17).

The area mapped in Figure 22 lies immediately south of that mapped in Figure 21. Here a single large outcrop of coarse pumice forms a 10-m-high, 150-m-long ridge whose structure consists of two anticlines and a syncline all trending parallel to the flow front. These folds are cut nearly at right angles by a series of fractures with separations that widen toward the flow front. This area has apparently undergone less extension than the area to the north, and so the width of separation along the individual fractures is not more than about 10 m. Foliations in the entire coarse pumice outcrop dip under surrounding adjacent outcrops of fine pumice, indicating a broad antithetic structure, but most of the contacts are obscured by blocks that have fallen off the ridge.

Figure 18. This 3-m-high outcrop shows a fine pumice crust which has been sandwiched between two parallel, fractured, coarse pumice diapirs. (a) Photograph; (b) foliation attitudes; (c) schematic representation. Arrows indicate directions of spreading and sites of compression.
Vent Area of the Northeast Lobe

Constructs such as Little Glass Mountain commonly consist of two parts: outlying flows with gently sloping upper surfaces and steeper-sided domes over the vent area. The vent area of the Northeast Lobe (Fig. 23) is a broad dome elongated along a N30°E axis, made up almost entirely of smooth-sided blocks of microcrystalline rhyolite. The dome is cut by deep fractures that have a radial pattern near the center of the dome. The deepest fractures in the summit area trend about N60°W. Foliations are generally steeply dipping and are truncated nearly everywhere by the smooth surfaces of the rhyolite outcrops. Shallow dips are found only near the bases of some of the fractures, and these gradually steepen upward, becoming vertical at the top of the fracture (Fig. 24). Strikes of foliations in the vicinity of the deepest fractures in the summit trend approximately parallel to them (N60°W), whereas foliations farther from the summit are oriented parallel to the elongated axis of the dome (N30°E). Stereoplots of poles to foliations (Fig. 25) clearly demonstrate these relations.

Extending down the east side of the dome, there is a series of regularly spaced ridges as much as 50 m wide, 1 to 3 m high, with a spacing of 3 to 5 m, which trend perpendicular to the downslope direction (Fig. 26). Foliations strike parallel to the crests of these ridges, dip steeply, and are

Figure 20. Map of portion of Northeast Lobe. In this and following maps, structures were determined from detailed measurement of foliation orientations and from topography. Folds are indicated by standard symbols. Axes of fractures are shown by solid lines with single or double cross bars, depending upon amount of lateral spreading associated with fracture growth. Single bar = less than 5 m spreading; double bar = greater than 5 m. Farthest extent of fracture surfaces marked by pairs of dotted lines. Contacts dashed where obscured by fallen blocks.
Figure 21. (a) Map of part of Northwest Lobe. Location of measured profile indicated by “N–S.” (b) Measured profile across part of Northwest Lobe. Obsidian (ob) outcrops originally overlie and are subsequently pushed apart by coarse pumice (cp) diapirs. No vertical exaggeration.

truncated by the smooth surface of the flow.

Three aspects of the foliation pattern require explanation: the steep dips, truncation by smooth surfaces, and the change of strike direction away from the central vent area. As flow banding generally forms parallel to a fixed surface like a conduit wall or underlying topography, the truncated fusions indicate that the smooth surfaces are fractures. The observed pattern could result if fracturing accompanied magma upwelling (Fig. 27). The two opposing surfaces of the fracture could then rotate away from the crack axial plane until most of the exposed foliations had near-vertical dips. Solidification of the fracture surface would preserve the vertical dip, and the viscous material beneath could flow laterally, compressing the surface into folds like those in Figure 26.

The strike directions of foliations can be explained by a two-stage emplacement. The lava initially came up through dikes oriented N30°E, parallel to prominent
The change in prevailing foliation direction could reflect changes in the state of stress of the volcano during the course of a single eruption or during a hiatus between two successive extrusive events. Alternatively, this change could indicate modifications in the vent geometry caused by explosive events or obstruction by congealed lava.

Preliminary examination of other domes near Big Glass Mountain in the Medicine Lake Highland and near South Sister Volcanic in Oregon shows similar concentrations of foliation orientations. At both of these locations, more than a dozen domes are arranged along linear trends. The preferred orientation of foliations in the domes lies parallel to those directions that correspond to either a local or regional structural trend. Furthermore, relatively low lying smooth areas in the centers of the domes are also elongated parallel to the distribution of the domes. These preliminary observations suggest that the structure of some individual domes may reflect regional structural trends and/or the shape of the magmatic conduit system. On the basis of surface structure, most of these domes appear to have been extruded through elongated vents rather than from pipe-like point sources of magma.

Mapping foliations exposed on the surface and within fractures in fresh domes such as those in the crater of Mount St. Helens might help delineate the geometry of their plumbing systems. The distribution of earthquake epicenters in the vicinity of Mount St. Helens in the three months following the May 18, 1980, eruption (Weaver and others, 1981) showed a strong preference for the same north-south trend on which the domes align. Recognition of changes in orientation of foliations and fractures in lava domes with time could indicate the directions in which future extrusions were likely to occur or where near-surface magma bodies might reside.

**Interpretation of Older Flows**

The surface structural information derived from Little Glass Mountain was obtained under conditions of optimum exposure. Even so, it was first necessary to recognize the initial configuration of the flow and then identify various deformational processes that disrupted the original stratigraphy. On older flows, both of these steps are made difficult by weathering effects. Over millions of years, glassy lavas tend to devitrify, accompanied in some cases by the growth of spherulitic textures. Vesicles in pumice units can be filled by secondary minerals, but the glassy septa also undergo devitrification. However, some vestiges of textural differences may still be discernible on the bases of color, specific gravity, and degree of crystallization. Foliations are commonly preserved in older flows, and these can aid greatly in the interpretation of flow deformation. Although the detailed foliation patterns on a flow can be exceedingly complex due to the interaction of diapirism, folding, and fracture, mapping the gross distribution of these structural markers can give a general indication of the flow direction and, in some cases, the vent location. This recognition is facilitated by comparison with fresh flows where the outcrops are nearly continuous and the original textures can still be identified.

Rhyolite flows and domes can signify either the beginning or the end of a particular cycle of volcanic activity. They are commonly found interlayered with mafic-flow and pyroclastic-flow deposits in caldera-filling sequences, as in the Superstition Mountains of Arizona (Sheridan, 1978). In other locations, such as the Coso Volcanic field (Bacon and others, 1980), domes are thought to be indicators of incipient explosive volcanism. In either case, it is useful to identify the proportions of pumiceous to nonvesicular lava in different domes within a field, in order to determine how the relative volatile contents of extrusions increase or decrease in time and space. Furthermore, the recognition of vent locations and alignments can help specify the tectonic stress fields in effect during the eruptive activity. Finally, mineralization of rhyolitic terranes is commonly associated with the migration of magmatic volatiles. Understanding the distribution of the various textures in young flows and their relation to volatile partitioning can assist in the evaluation of ore deposition in older rocks.

**SUMMARY**

Little Glass Mountain is a 300- to 1,100-yr-old, chemically homogeneous, rhyolitic obsidian dome and flow complex that has been subjected to negligible postemplacement alteration. The distribution of textural rock types and the foliation patterns observed on the flow surface reflect both the initial stratigraphy of the flow and its subsequent deformation during emplacement.
Figure 23. Map of vent area, Northeast Lobe, showing a sampling of foliation attitudes. Topographic break separates dome where rock type is primarily microcrystalline rhyolite, from outlying flow where the surface is composed mostly of fine pumice. Dashed line separates inner region where foliations are influenced by N60°W fracture, from outer, earlier-emplaced region where orientations are controlled by N30°E fractures (see Fig. 25).
Figure 24. (A) View along N60°W-trending fracture in vent area of Northeast Lobe. Dips of foliations gradually decrease from near vertical at tops of outcrops to horizontal near the base. View to the northwest. Largest blocks are about 5 m high. (B) Tracing of foliations from photo above (A).

Figure 25. Stereoplots of poles to foliations from large outcrops in vent area of Northeast Lobe. One measurement taken near top of each outcrop. (a) Plot for inner zone surrounding prominent N60°W fractures. (b) Plot for outer zone, showing preferred orientation around N30°E.

Figure 26. Folded smooth-fracture surface near vent area of Northeast Lobe. Fold spacing about 3 m, amplitude about 1.5 m. Flow direction from right to left. View to south.
The stratigraphy includes a surface layer of finely vesicular pumice, a central layer of glassy obsidian, a basal layer of coarsely vesicular pumice, and an underlying contemporaneous air-fall tephra deposit. This sequence may be caused by a decrease in the volatile content of the magma during the course of its eruption.

Three deformational processes disrupt the initial layering of the lava flow as it advances, and these are reflected in the surface structure of the flows. Diapirs of low-density, coarsely vesicular pumice rise from the base to the surface of the flow and appear as domes and plunging anticlines with regular spacings in the flow direction. Flow-parallel compressive stresses near the flow front and at sites of constriction produce long, regularly spaced surface ridges or folds oriented transverse to the flow direction, which cut across textural contacts. At sites of extension, surface fractures propagate inward due partly to thermal contraction of the cooling flow and partly to the rise of coarse pumice diapirs. These three processes interact to produce the wide range of complex surface structural relations observed on this and other Holocene rhyolite flows and domes.

The final eruptive product at Little Glass Mountain was lava of slightly higher viscosity, which piled up over the vent area. As this magma emerged, it was split by downward-propagating fractures. New fracture surfaces with steeply dipping foliations continued to develop and were transported laterally away from the vent by the underlying flowing lava, so that eventually large areas of the dome became covered by these fracture surfaces. Subvertical foliations in these summit domes partly reflect the geometry of the fractures, which in turn may correspond to the orientations of the feeding vents. Mapping these foliations in older flows may help in the interpretation of the eruptive history of a particular eruption and in the evaluation of likely sites of future activity and residual hot magma.

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