Journal of Non-Crystalline Solids 67 (1984) 135–146
North-Holland, Amsterdam

STRUCTURAL GEOLOGIC CONSTRAINTS ON THE RHEOLOGY OF RHYOLITIC OBSIDIAN

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Laboratory measurements of the rheology of volcanic glasses may be supplemented with estimates obtained from field measurements of structures on natural obsidian lava flows. These viscosity values reflect the textural heterogeneity of volcanic glasses, which are often overlooked in laboratory determinations. By mapping the distribution of different pumiceous and glassy textures, patterns may be observed that can be interpreted using a variety of deformational models large scale surface folds indicate the ratio of surface to interior viscosities; the regular spacing of pumice diapirs reflects the relative viscosities of glassy and pumiceous zones, and the depth and form of fractures are controlled by thermal and elastic properties of the lava. Small scale structures such as folds and boudinage indicate that obsidian layers have a pseudoplastic, power law rheology, a finding confirmed by recent laboratory studies

1. Introduction

Knowledge of the rheological properties of natural silicate glasses is necessary for the evaluation of hazards associated with volcanic eruptions, for understanding the evolution of magma bodies, and for the interpretation of meteorite glasses. It can also provide useful insights into processes involved in the manufacture of artificial glasses. Most of the rheological information comes from laboratory studies (e.g., [1–4]), which have indicated that the slightly non-Newtonian viscosity of natural silicate melts is a function of their water content, silica content, temperature, and pressure.

Natural glasses usually contain inhomogeneities such as bubbles and crystals, which alter their rheologic behavior. Only limited data are available on the effects that crystals and bubbles have on the viscosity of volcanic glasses so that the actual rheology of either subsurface or subaerial flowing silicic magma may be only approximated by laboratory measurements. However, structures on the surfaces of obsidian lava flows constitute a type of natural rheologic laboratory from which the effective bulk rheological properties of volcanic glass containing various types of inclusions may be inferred.

Deformational models, although less precise than laboratory measurements, may indicate the influence of inhomogeneities such as bubbles and crystals, and may take account of cooling effects. The purpose of this paper is to describe a few types of structure found on natural rhyolitic obsidian and pumice lava flows, and to discuss their usefulness as quantitative and qualitative indicators of rheologic behavior.

2. Deformational behavior of obsidian and pumice

Before describing the structures used to estimate the rheologic properties of natural volcanic glasses, I will briefly consider some of the general aspects of their deformational behavior. Depending on various conditions such as temperature, pressure, and strain rate, obsidian and pumice may exhibit elastic, linear or non-linear viscous, or brittle behavior. The following discussion is not meant to be exhaustive, as many recent studies are omitted; rather it serves as a point of departure for the subsequent descriptions.

At low temperatures or stress levels, obsidian deforms elastically [5], according to Hooke's Law:

$$\sigma = E\epsilon,$$

where E is the Young's Modulus, σ is the stress, and ϵ is the strain. In foliated obsidian, E is slightly dependent upon the angle between the applied stress and the flow structure, with the highest rigidity occurring for stress applied parallel to layering. E is relatively insensitive to rising temperature up to about 700°C, at which point it drops rapidly. This glass transition temperature is the point at which obsidian begins to deform as a viscous fluid; for most glasses it corresponds to a viscosity of about 10^{13} poises (10^{12} Pa s) [2].

Viscous behavior is characterized by a time-dependent response to stress:

$$\sigma = \eta\epsilon',$$

where η is the coefficient of viscosity and ϵ' is the strain rate. Above the liquidus, viscosity decreases with increasing temperature according to the relation:

$$\eta = A \exp(E/RT),$$

where A and E/R are constants, and T is absolute temperature. Viscosity also decreases with increasing water content. Equilibrium water content depends in turn upon temperature and pressure [1]. The water content of obsidian in the flows to be discussed is generally in the range of 0.10 to 0.12 wt% [6].

Obsidian and pumice layers within a single lava flow commonly have nearly identical chemistry [7] so that mechanical 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 [8]. The viscosity of a froth, measured by Sibree [9], was found to be a function of the volume percent of bubbles. Viscosity increased by up to two orders of magnitude up to a porosity of 70%. Observations made during the heating of water-rich obsidians in the laboratory indicate that the viscosity of the lava decreases during the actual process of frothing, but that after the gases are liberated, the froth becomes rigid and resists further deformation. Upon heating, the septa in a froth collapse, allowing the lava to flow again [6].

The presence of steep fronts and levees along the margins of most lava flows has been interpreted as evidence that the lavas possess a yield strength [10–12], which is a quantity of stress that must be exceeded before the lava can begin to deform:

$$\sigma = \sigma_y + \eta_p \epsilon',$$

where σ_y is the yield strength and η_p is the plastic viscosity [13]. Like viscosity, yield strength decreases with increasing water content, temperature, or silica content [14]. Above its liquidus, obsidian has a negligible yield strength, but as it cools during emplacement its strength increases.

Under certain conditions, lava responds to an applied stress by fracturing rather than flowing. When local tensile stress equals the tensile strength (σ_t) of the lava, brittle failure occurs. For a deforming lava, an increase in either strain rate or viscosity could cause the stress to approach and exceed the tensile strength. Slight variations in either parameter can cause fracture and flow to occur nearly simultaneously. This intimate association helps explain several of the structural relations observed on obsidian lava flows.

The linear elastic and viscous models cited above are simplifications which describe only the most general aspects of the deformation of obsidian and pumice. For example, the apparent viscosity of froths measured by Sibree [9] was found to decrease with increasing shear rate, approaching a constant value at the highest rates. The nonlinear behavior in which viscosity decreases with increasing strain rate is termed pseudoplastic and may be represented by the Ostwald–de Waale model [15]:

$$\sigma = -m|\epsilon'|^{n-1}\epsilon'; \ (n < 1),$$

where m and n are constants and where m equals the viscosity for the special case of $n = 1$. The additional constraint that the viscosity approaches a constant value at high strain rates requires the still more general Ellis model:

$$-\epsilon' = \left(\psi_0 + \psi_1|\sigma|^{\alpha-1}\right),$$

where ψ_0, ψ_1, and α are constants. These and other complex rheological behaviors were described by Shaw [2] and Shaw et al. [13] for viscosity measurements of obsidian and basalt. More recently, Spera et al. [4] demon-

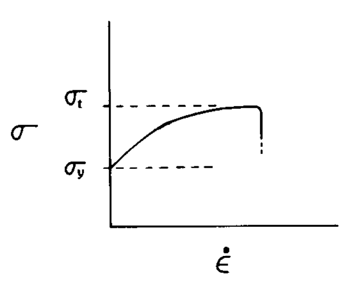
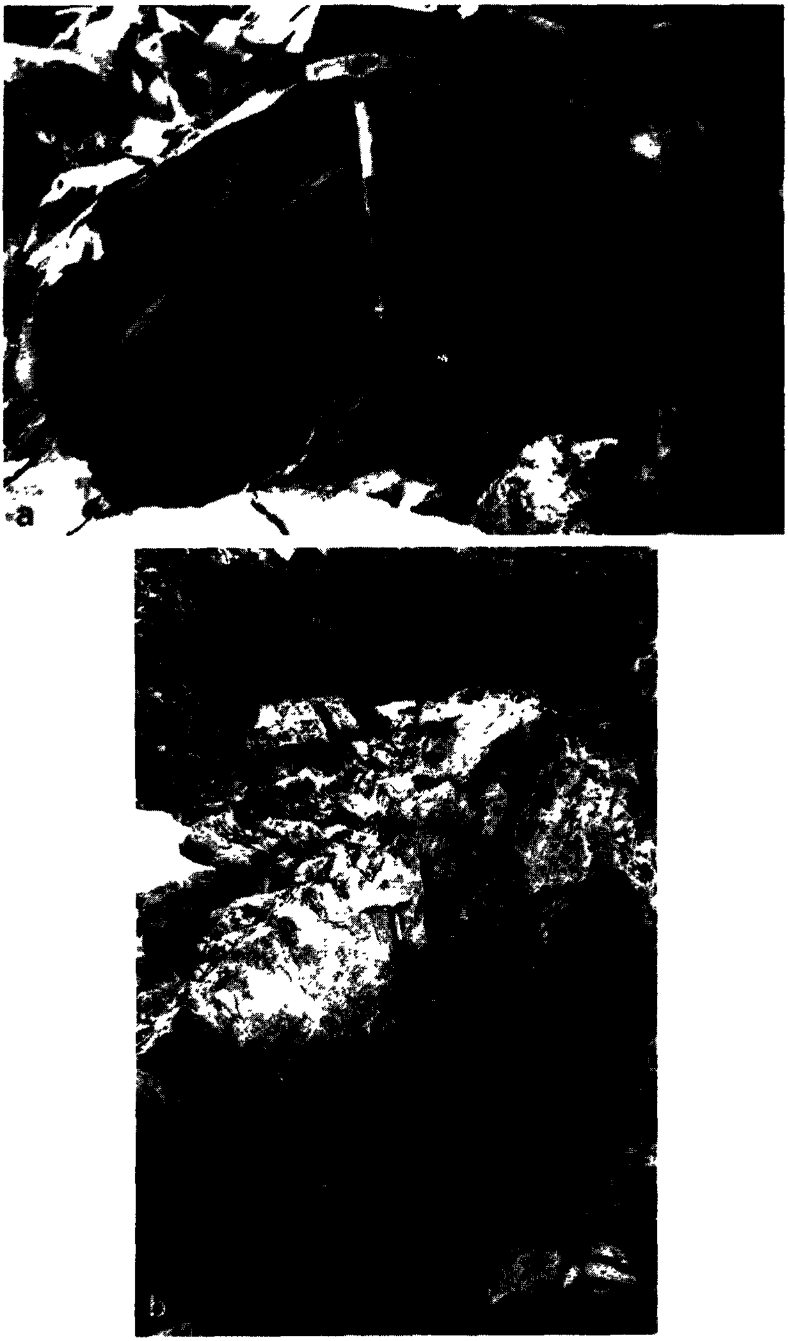


Fig. 1 Hypothetical curve of stress (σ) versus rate of strain ($\dot{\epsilon}$) for lava possessing yield strength (σ_y), tensile strength (σ_t), and pseudoplastic behavior. Brittle failure occurs when stress reaches tensile strength (from [16])



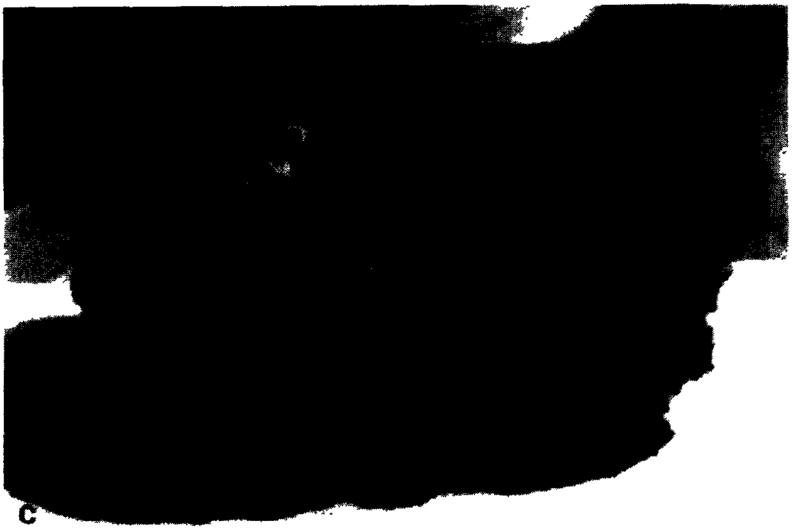


Fig. 2 Obsidian and pumice textures (a) Flow banded obsidian (b) Sample of obsidian grading upward into finely vesicular pumice (c) Coarsely vesicular pumice (from [16])

strated that rhyolite magma at a temperature of 1125°C exhibits pseudoplastic behavior with a power law exponent of 1.25. These non-linear effects are generally overlooked in rheologic interpretations of geologic structures due to a lack of sufficiently accurate field data.

Based on laboratory data, obsidian and pumice may thus be considered to have rheological properties which depend upon strain rate, temperature, and volatile content. In general, the lava deforms according to a stress–strain rate curve of a type shown schematically in fig. 1. For $\sigma < \sigma_y$; the lava deforms elastically:

$$\sigma = \epsilon E$$

For $\sigma_y < \sigma \ll \sigma_t$, the lava flows according to:

$$\sigma = \sigma_y + m|\epsilon'|^{n-1}\epsilon'.$$

As σ approaches σ_t, strain increases very rapidly until fracture occurs.

3. Geologic background

Rhyolitic obsidian flows are commonly erupted during the last stages of an explosive volcanic episode, after most of the magmatic volatiles have already been driven off. Volatiles that remain are emplaced as pumiceous zones interspersed with the obsidian. Fig. 2 shows three of the most common textures found in rhyolitic obsidian flows. Fig. 2a is a glassy obsidian that is virtually bubble-free. The banding is caused by varying concentrations of feldspar crystallites: lighter bands are crystal-rich; darker ones crystal-poor. Rheologic behavior of this glassy lava texture probably comes closest to that measured in the laboratory. Figs. 2b and 2c show two different pumice textures. Fig. 2b is a coarsely vesicular pumice that is generally emplaced at an early stage and hence is located near the base of the flow. Fig. 2c shows a finely vesicular pumice that exsolves from the obsidian at a late stage near the upper flow surface.

The distribution of these textures in an obsidian flow commonly shows a consistent stratigraphic arrangement, with the obsidian sandwiched between finely vesicular pumice above and coarsely vesicular pumice below. Fig. 3 shows an aerial view of Little Glass Mountain, an 1100 year old rhyolitic obsidian flow in northern California [16]. The dark areas are composed primarily of coarsely vesicular pumice, whereas the light areas are made up of finely vesicular pumice. Obsidian comprises the core of the flow and is not

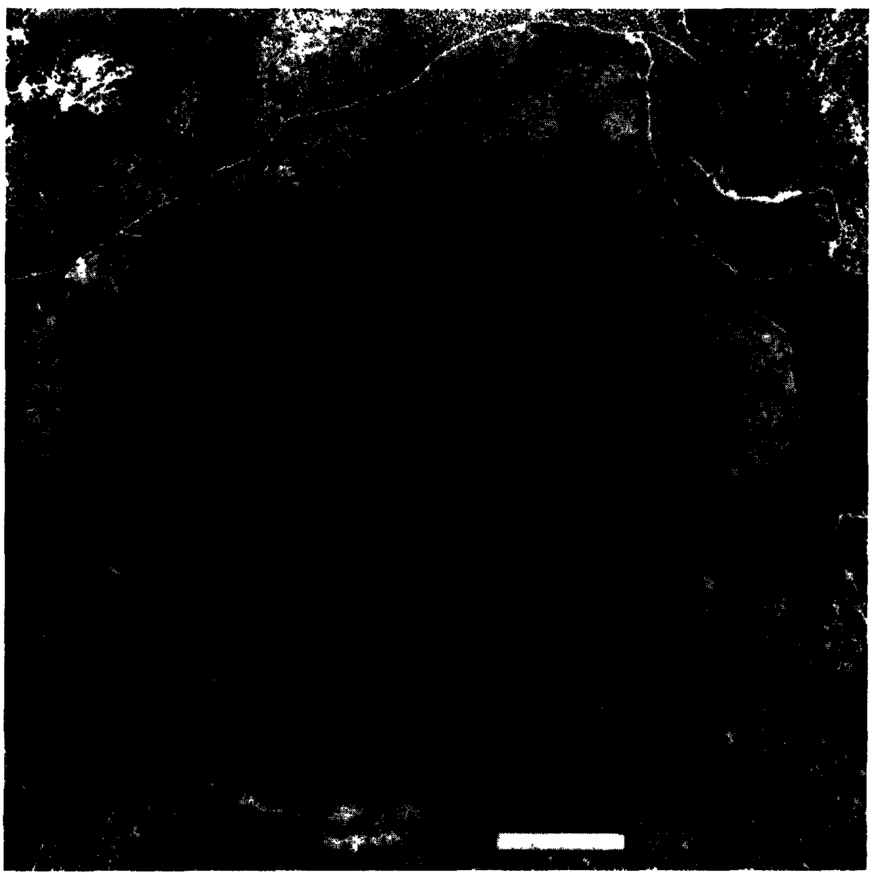


Fig. 3 US Forest Service Photograph of Little Glass Mountain rhyolitic obsidian flow, northern California. Scale bar = 500 m. North is to top (from [16]).

widely observable on the upper surface. In this photograph we can observe two of the large scale structures used to estimate rheologic properties: surface folds and pumice diapirs.

The surface of several flow lobes of Little Glass Mountain are crossed by extensive anticlinal ridges stretching from margin to margin, parallel to the flow front (fig. 4). Such ridges constitute a type of fold that may form on the surface of any fluid whose viscosity decreases with depth, when that fluid is subjected to sufficiently strong compressive stress. The spacing of the ridges indicates the viscosity gradient near the surface of the flow, as well as the magnitudes of the compressive stresses [17]. In flows for which the stresses can be approximately determined, the interior viscosity may be estimated from the ratio of ridge spacing to ridge amplitude [18]. For example, measurements of ridge spacings on obsidian flows in California yielded minimum viscosity values of 10^{11} P (10^{10} Pa-s), which are at least two orders of magnitude higher than comparable laboratory values for anhydrous obsidian. However, these crude estimates are for the effective rheology of the entire upper flow, which includes pumice and obsidian in both massive and loose, blocky forms. The presence of angular blocks capable of interacting and restricting advance of the flow fronts is primarily responsible for this higher effective viscosity for the obsidian [1,19].

The second type of large scale structures found on the surfaces of obsidian flows are regularly spaced, circular to elliptical outcrops of scoriaceous pumice

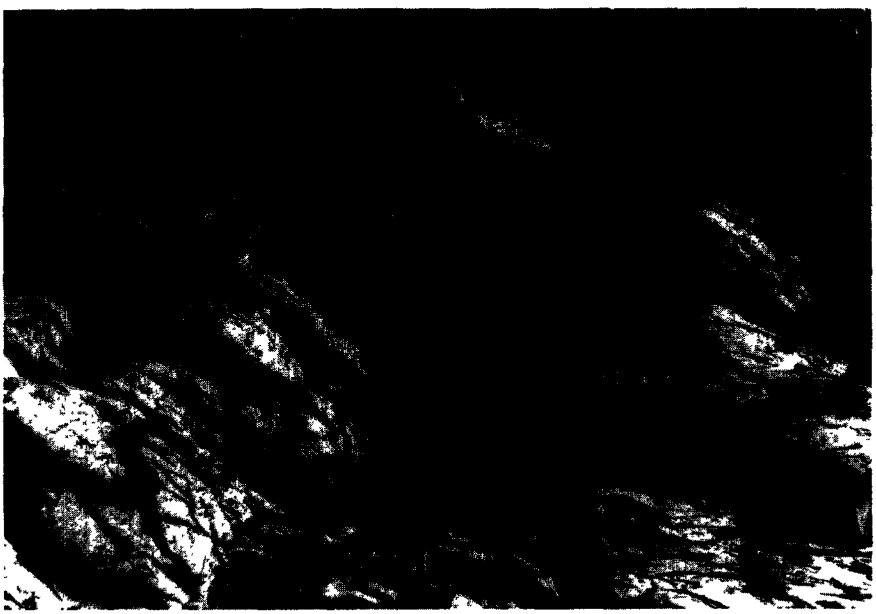


Fig. 4. Compressional folds in obsidian flow surface, Little Glass Mountain. Fold spacing about 3 m, amplitude about 1.5 m. Flow direction from right to left. View to south (from [16])

that range up to 30 m in diameter. The outcrops, seen on the western and northeastern lobes of Little Glass Mountain (fig. 3) are diapirs that rise from the interior or base of the flow due to density contrasts inherent to the stratification of pumiceous zones within an obsidian flow. The rheological significance of these diapirs comes from the relationship between their spacing and the relative viscosities of the layers of contrasting density. By measuring the spacing of diapirs (10 to 50 m) on obsidian flow surfaces and the stratigraphic thicknesses (5 to 35 m) of layers in flow fronts. Fink [20] found that the viscosity ratio between layers of pumice and bubble-free obsidian ranged from 50 to 100, indicating that vesicles in the pumice acted to increase rather than decrease its bulk viscosity. Such ratios are consistent with experimental observations of froth viscosities cited earlier.

A third type of surface structure that reflects the bulk rheology of obsidian flows are fractures up to 5 m deep that generally trend perpendicular to the flow fronts (fig. 5). Each of these cracks is composed of a pair of outwardly convex surfaces that contain numerous small steps or striae ranging from a few mm to a few cm. These fractures form when local tensile stresses exceed the tensile strength of the cooling, laterally spreading lava flow. The fractures penetrate to a depth controlled by the thermal structure of the flow. As fractures propagate inward, isotherms are deflected in the underlying lava, causing fluid regions to lie adjacent to the cooled fracture surfaces. The fluid regions respond to the weight of the overlying, fractured lava by flowing away laterally, resulting in the convex shape. Inward propagation of the crack

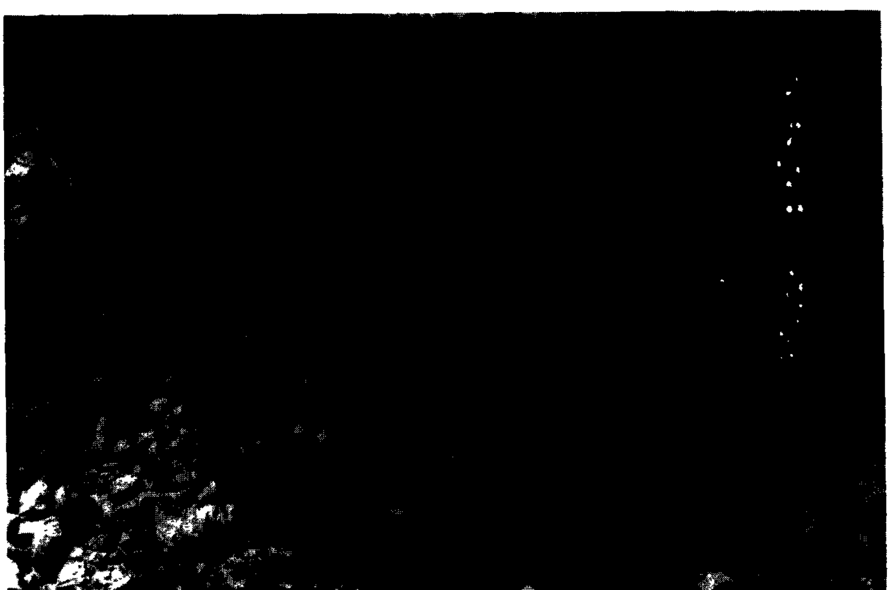


Fig 5. 3 m-deep fracture cutting through a series of coarsely vesicular pumice outcrops. Fracture axis parallels flow direction (from [16])

Fig. 6 Step-like striations on fracture surface in finely vesicular pumice sample Fracture propagated from right to left

proceeds episodically [21], as the crack front advances more rapidly than the thermal front. The episodic nature of the crack growth is reflected in the step-like form of the fracture surfaces (fig. 6). Measurement of similar steps in basalt flows allowed estimation of the glass transition temperature and thermal and elastic parameters [21]. Ryan and Sammis [21] inferred from basalt fracture morphology that a supercooled melt/grain boundary phase helped regulate the cracking process. Shallower temperature gradients and the absence of crystals in rhyolitic obsidian flows limit the direct application of Ryan and Sammis' model; however the same general processes may be expected to occur in rhyolitic obsidian flows as well.

4. Small scale structures

Structural geology text books commonly show pictures of obsidian in their discussions of flow-folds. Indeed, highly contorted folds are found widely in certain portions of obsidian lava flows, particularly near flow margins and at contacts between zones of contrasting texture. In most flow-folded obsidian, the foliation or flow banding serves as a passive marker recording the changing directions of maximum compressive stress experienced by a nearly homogeneous lava sample as it is carried downstream. The structures can thus be described as multiply refolded folds. The strain history of such samples generally cannot be deciphered.

Less complicated folds within obsidian and pumice layers potentially contain more precise rheologic information. In any lava flow, compression may occur whenever or wherever the flow decelerates. Layered viscous media with contrasting material properties can produce regularly spaced folds when subjected to such layer-parallel compression, with fold wavelengths reflecting the ratio of layer viscosities [e.g., 22,23]. However, wavelength-to-thickness ratios less than about 10 only occur for layers with pseudoplastic, power law rheologies whose values of the exponent n are greater than about 4 [24].

Isolated layers of either pumice or obsidian may be found sandwiched between zones of the other texture on Little Glass Mountain and other flows. When compressed into folds, these multilayers generally exhibit wavelength to thickness ratios less than 10 (fig. 7). Such relatively short wavelengths could be caused by local gravity instabilities, but in that case the fold forms would not be symmetric. Other possibilities are that these wavelengths could result from internal flow within the layers. In that case the folds should appear thickened in the hinges and thinned in the limbs. The uniform thicknesses of the fold layers and their symmetric forms both indicate that the short fold wavelengths were caused by pseudoplastic rheological behavior, consistent with the measurements of Spera et al. [4].

Certain portions of lava flows undergo extension as well as compression, resulting in a different set of possible structures. Multilayers subjected to layer-parallel extension respond by either uniformly thinning or by necking to form pinch and swell structures. Like short wavelength folds, unstable necking

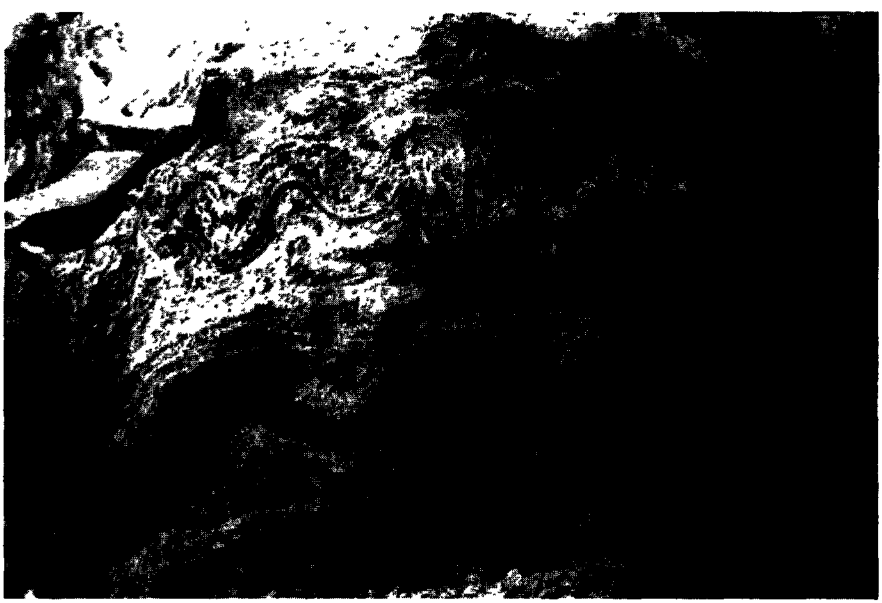


Fig. 7. Small concentric folds of obsidian layers embedded in coarsely vesicular pumice. Fold wavelength approximately 10 cm; layer thickness approximately 1.5 cm.

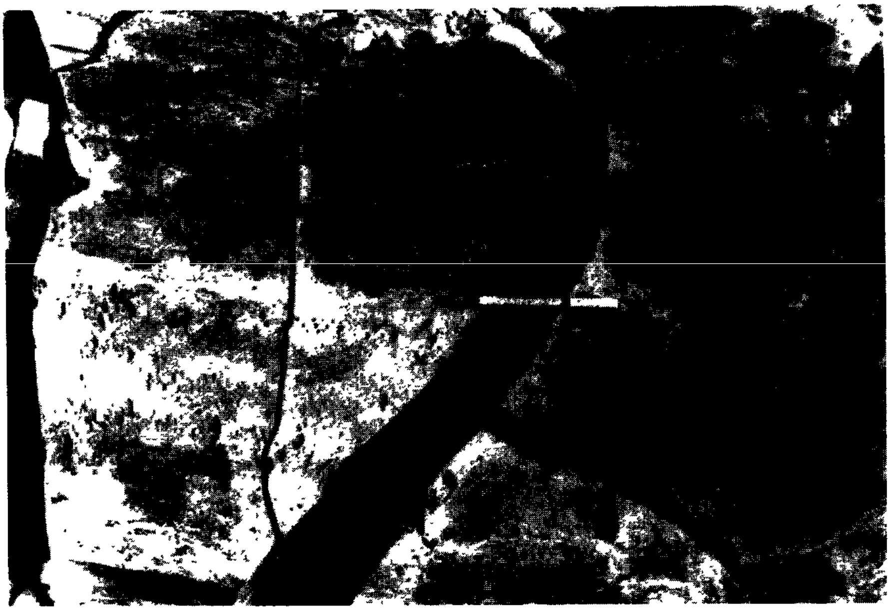


Fig 8. Tensile fractures within crystallite-rich layers embedded in obsidian. Ball point pen for scale

requires layers with pseudoplastic behavior, whereas newtonian layers thin evenly [24]. During necking, if local layer-parallel strain rates exceed the tensile strength, regularly spaced tensile fractures will develop.

Various examples of unstable necking phenomena can be observed on obsidian flows. Fig. 8 shows the surface of an obsidian block that underwent layer-parallel extension. Thin bands slightly enriched in feldspar microlites apparently had somewhat lower tensile strengths since they fractured while the surrounding obsidian layers flowed. The periodic spacing of these tension gashes in the crystallite-rich layers indicate that an unstable necking process preceded the fracturing events. Such behavior also suggests that the obsidian had a pseudoplastic rheology.

5. Summary

Available laboratory information on the rheology of volcanic glasses primarily concerns the behavior of inclusion-free obsidian. Natural volcanic glasses may have bubbles and crystals that give different bulk properties from those measured in the laboratory. Studies of the deformation of obsidian flows can provide additional information about the rheologic behavior of these glasses.

Large scale surface folds, pumice diapirs, and paired fractures indicate the relative viscosities and thermal properties of surface and interior phases. The finely vesicular pumiceous carapace of the flow has a viscosity approximately

10–35 times greater than that of the bubble-free interior [18]. In contrast, the basal pumice layer has a viscosity 50 to 100 times greater than that of the interior obsidian [20]. By measuring bubble concentrations in the different pumiceous layers, one could obtain an expression for pumice viscosity as a function of vesicularity. By noting the depth of penetration of surface fractures as a function of distance from the vent, and assuming a certain flow rate, one could estimate the cooling rate of the flow surface and hence infer the thermal conductivity and other properties.

Small scale structures such as boudinage and folds with wavelength-to-thickness ratios less than about 10 are best explained by assuming a pseudo-plastic power law rheology for the obsidian and pumice layers. This nonlinear behavior may be due to interaction of the elongate feldspar microlites found in some of the obsidian layers, or may be caused by the presence of deformable bubbles in the pumiceous layers.

Further studies of this type will be directed toward a better understanding of the mechanics of fracture and flow in natural glasses, with possible application to the mechanical behavior of artificial glasses.

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