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Case study of an extensive silicic lava: the Bracks Rhyolite, Trans-Pecos Texas

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Abstract

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Field, petrographic, and chemical data indicate that the Bracks Rhyolite of western Trans-Pecos Texas is a single lava flow that traveled as much as 35 km from a source in the north-central part of its outcrop. With a minimum original extent of 1000 km^2 and volume of 75 km^3, the Bracks is far more extensive and voluminous than typical silicic lavas. The Bracks crops out in a 55 × 16 km north-trending belt. It thins radially from a maximum thickness of about 120 m. However, except at flow margins where it thins abruptly, it is everywhere at least 25 m thick. Clusters of vitrophyric domes that intrude and are otherwise identical to the dominantly crystalline lava may represent diapiric rise of hotter, less dense, lower parts of the flow. Some domes may overlie fissure vents that fed the flow. The source area is in the north-central part of the flow, on the basis of thickness and flow patterns and distribution of vitrophyric domes. The Bracks is a slightly peralkaline low-silica rhyolite or trachydacite (68–69% SiO_2). Whole-rock analyses for major oxides and rare earth elements and microprobe analyses of alkali feldspar, Fe-rich clinopyroxene, fayalite, and magnetite phenocrysts show that the Bracks, including vitrophyric domes, is chemically and mineralogically homogeneous, both laterally and vertically.

Evidence that the Bracks was emplaced as a lava flow includes autobreccia at the base and top, steep flow fronts, abundant flow bands and folds, elongate vesicles, trachytic texture, and groundmass textures that indicate crystallization from a liquid. Basal breccia that occurs throughout the extent of the flow, is uniformly coarse, and varies in thickness laterally can only form from a lava that flowed over its entire extent. Evidence of a pyroclastic origin, such as shards, pumice, lithics, or welding zonation, is absent. The low aspect ratio of the Bracks (approximately 1 : 500), although in a range typical of many ash-flow tuffs, is considerably higher than that of unequivocal tuffs in Texas, which have comparable outcrop areas but are much thinner.

The great extent and sheet-like geometry of the Bracks probably reflects high eruption temperature (≥ 900°C), low volatile content, moderately low viscosity, rapid eruption, and slow cooling. Unusually low viscosity, on the order of basaltic lavas, was not a factor because, despite peralkalinity and high temperature, the Bracks probably had a low volatile content.

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Introduction

Many silicic volcanic rocks worldwide have the outcrop and textural characteristics of lavas but the wide extent and low aspect ratio considered typical of ash-flow tuffs (Cas, 1978; Twist and French, 1983; Ekren et al., 1984; Bonnichsen and Kauffman, 1987; Henry et al., 1988). The origin of these rocks is controversial; they may be true lavas or ash-flow tuffs that underwent such extreme primary or secondary (rheomorphic) laminar viscous flow that pyroclastic features are obliterated (Ekren et al., 1984; Bonnichsen and Kauffman, 1987; Henry et al., 1989; Milner and Duncan, 1989; Twist et al., 1989). Determining the origin of these rocks is important for a variety of reasons, including interpreting ancient volcanic successions, understanding eruption and flow mechanisms, and assessing volcanic hazards.

Silicic extrusive rocks having great areal extents but the characteristics of lavas are strikingly developed in Trans-Pecos Texas, particularly in and around the Davis Mountains (Fig. 1). Although strongly rheomorphic tuffs also occur in Texas, this report focuses on the extensive silicic lavas. The Bracks Rhyolite is the best exposed and currently most thoroughly studied of a group of three extensive silicic lavas that include the Star Mountain Formation and Crossen Trachyte (Gibbon, 1969; Twiss, 1971; Henry et al., 1988, 1989; Franklin et al., 1989; Parker, 1989). Despite different formational names, the three units are nearly indistinguishable in outcrop characteristics, phenocryst assemblage and abundance, composition, stratigraphic position, and age. New, high-resolution, $^{40}Ar/^{39}Ar$ ages on the three units (C.D. Henry and M.J. Kunk, unpubl. data, 1989) are indistinguishable at about 36.8 Ma. Uncertainty in the $^{40}Ar/^{39}Ar$ ages is such that the maximum difference in their ages can be no more than 0.25 Ma. The three units differ only in that the Bracks and Crossen appear to be single flows, whereas the Star Mountain consists of several similar flows (Parker, 1989). Henry et al. (1988) suggested that the three units represent a distinct event in the volcanic history of Trans-Pecos Texas.

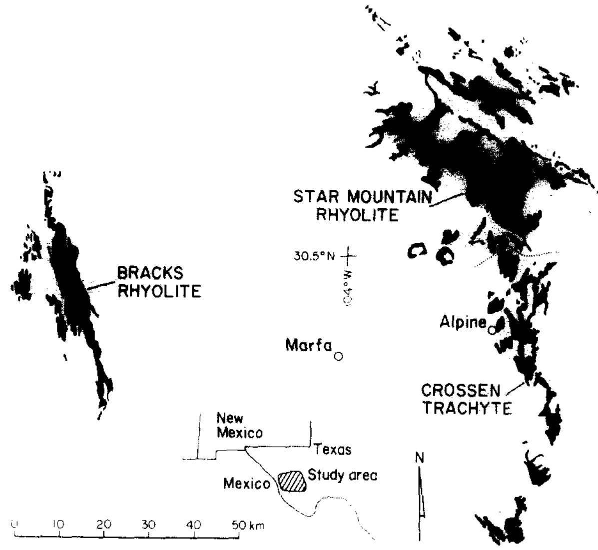


Fig. 1. Approximate outcrop of Bracks Rhyolite, Star Mountain Formation, and Crossen Trachyte and general location of the Trans-Pecos volcanic field. Bracks and Crossen are single lava flows; Star Mountain is a composite of several flows.

Because it is so well exposed and because field, petrographic and chemical data demonstrate that it is a single flow, the Bracks is an ideal example upon which to base criteria to evaluate other less well-exposed rocks. This report documents the characteristics of the Bracks Rhyolite, discusses the evidence that demonstrates its lava-flow origin, and attempts to identify the magmatic characteristics and eruption and emplacement mechanisms that allow a silicic lava to flow great distances. Results are applicable to interpretation of other silicic lava flows of great areal extent.

Outcrop, petrographic, and chemical characteristics

The Bracks Rhyolite occurs in the western part of Trans-Pecos Texas (Figs. 1, 2). It occurs within what we interpret to be a subduction-related,

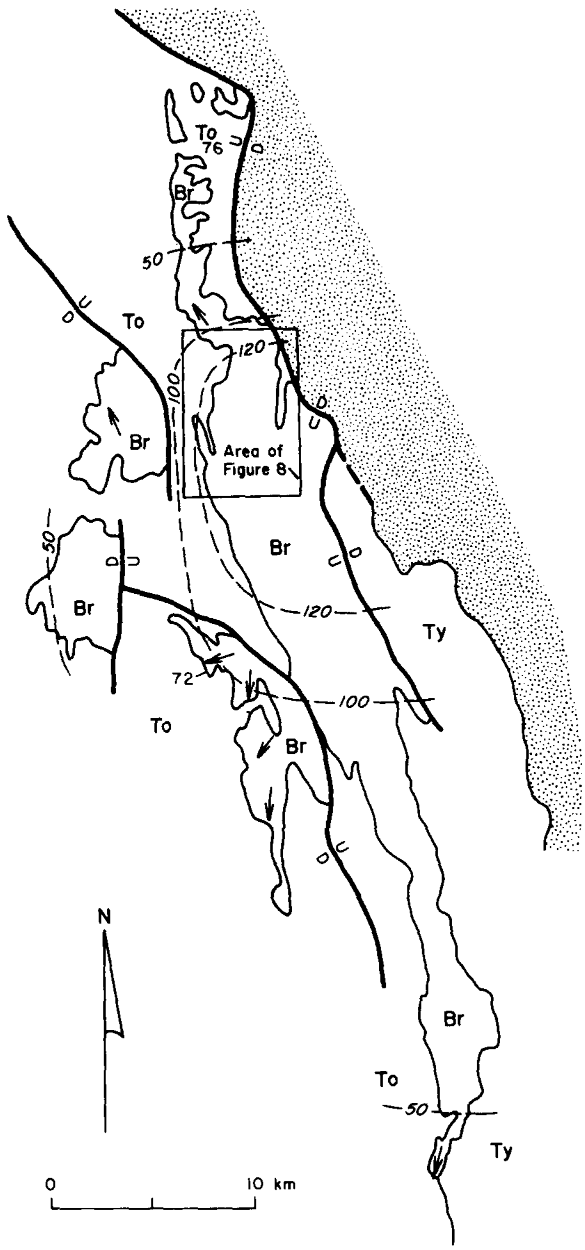


Fig. 2. Outcrop, thickness (meters), and flow directions (arrows) of Bracks Rhyolite (*Br*). Thickness and flow directions indicate preferential flow to the south from a source in the north-central part of the outcrop. *To* = older volcanic rocks; *Ty* = younger volcanic rocks; stipple = Upper Cenozoic basin fill. Outline indicates probable vent area depicted in Figure 8. Sample locations for chemical analyses (Table 1) are shown here and on Figure 8.

continental volcanic arc that is dominated by the products of major caldera systems (Henry and McDowell, 1986; Price et al., 1987). Neither the Bracks, Star Mountain, or Crossen are related to any calderas, however. The Bracks is part of the Vieja Group, which consists dominantly of tuffaceous sediments interbedded with lesser ash-flow tuff and lava. Tuffaceous sediments both underlie and overlie the Bracks throughout its distribution.

The Bracks is exposed in a continuous, 55-km-long north-trending belt (Figs. 2, 3A). Mostly it dips gently eastward, from a few degrees up to about 10°. The widest part of its outcrop is about 16 km, but the Bracks is buried on the east by Upper Tertiary sediments within a Basin-and-Range graben. Except on the east, the present outcrop probably approximates original distribution. For example, the southern end is a steep nose that appears to be a slightly eroded flow margin; trains of elongate vesicles curve continuously around the nose.

Exceptional exposure of the Bracks along its entire 55-km length demonstrate that it is a single flow. The west side of the main outcrop is an essentially continuous cliff face developed along a series of Basin-and-Range faults (Figs. 3A, B). The cliffs provide complete cross sections through the Bracks along its entire length. Exposures along the east side of the main outcrop and around the smaller outcrop areas are comparable. These faces reveal no internal breaks, laterally or horizontally, that could separate different flows. One outcrop along its southwestern margin apparently parallels the original flow front. In this location, the Bracks divides into several thick flow lobes, separated now by tuffaceous sediments.

Maximum preserved thickness is about 120 m in the north-central part of its outcrop (Figs. 2, 4). The flow thins gradually to the south and more abruptly to the north and west. However, except at flow margins where it thins abruptly, the Bracks is everywhere at least 25 m thick. For example, at the southern nose it thins from 40 to 0 m in a distance of 100 m. Original thicknesses

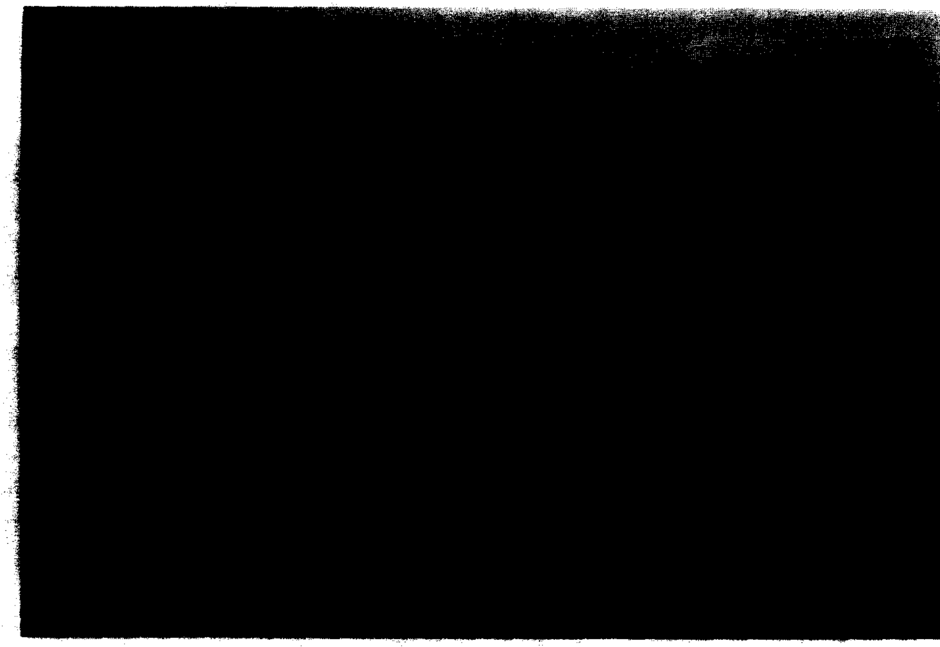


Fig. 3. (A) Looking north at southern end of Bracks outcrop (dark, massive flow overlying poorly exposed white tuffaceous sediments) exhibiting thin, sheet-like geometry. Disruption in foreground is due to a combination of minor faults and landslides. Bracks Rhyolite continues as caprock 55 km to north (left distance).
(B) Representative exposure of Bracks, approximately 100 m thick in this area, in continuous cliff face along eroded Basin-and-Range fault scarp.

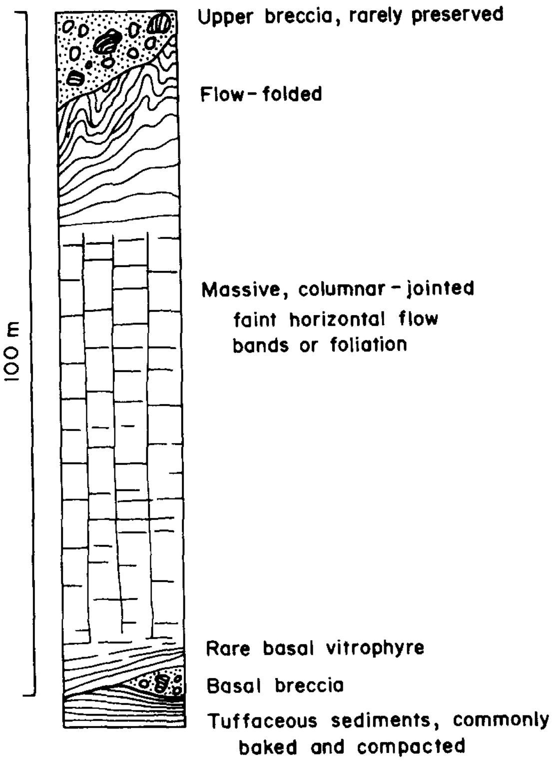


Fig. 4. Generalized section of Bracks Rhyolite, showing basal breccia, flow bands and folds, massive interior, crude columnar joints, and upper breccia.

were greater than preserved thicknesses because the flow is eroded to the top of its massive interior. Small patches of an upper breccia of unknown original thickness are locally preserved. The upper breccia may not have been thick, however, because the basal breccia is thin. Minimum volume is about 75 km^3. Aspect ratio is about 1 : 500 (Fig. 5).

Outcrop characteristics of the Bracks are typical of silicic lava flows (Figs. 4, 6; Fink, 1983; Fink and Manley, 1987; Manley and Fink, 1987). It rests in sharp contact on tuffaceous sediments, which are commonly baked, compacted, and silicified due to heating by the flow. Locally the sediments are deformed, probably as a result of loading; tongues of sediment extend a few tens of centimeters into basal breccia of the lava. No underlying primary pyroclastic material, such as surge or air-fall deposits that precede eruption of many silicic lavas (Fink, 1983), has been found.

A basal breccia as much as 2 m thick contains angular to subrounded clasts up to 1 m in diameter (Fig. 6B). The clasts include a mix of textural varieties (massive, flow-banded, vesicular) of Bracks in an indurated, commonly silicified matrix of finer fragments. The breccia is uniformly coarse. Breccia is absent in some places, and massive rock continues to the base. Either breccia was never deposited at these locations, as with some mafic lavas (Wentworth and Macdonald, 1953; Green, 1989), or continuous heating rehomogenized the base as the extensive flow passed over it (C.R. Manley, pers. commun., 1989).

Massive interior (Fig. 6A), which makes up most of the flow, overlies the breccia or tuffaceous sediments where breccia is absent. Flow bands are variably defined by crystallization differences, minor color differences, discontinuous partings, aligned phenocrysts, or trains of elongate vesicles. They range from faint to well

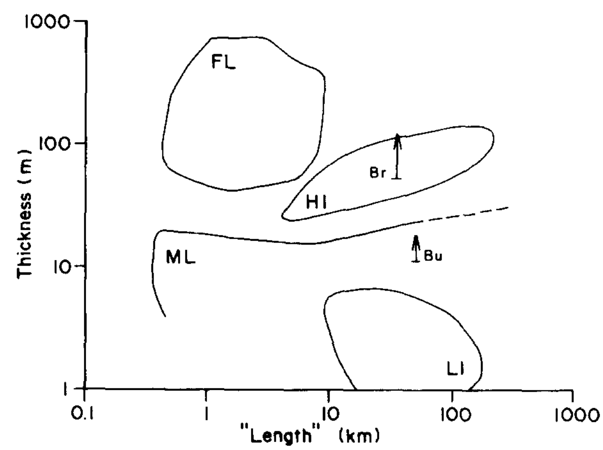
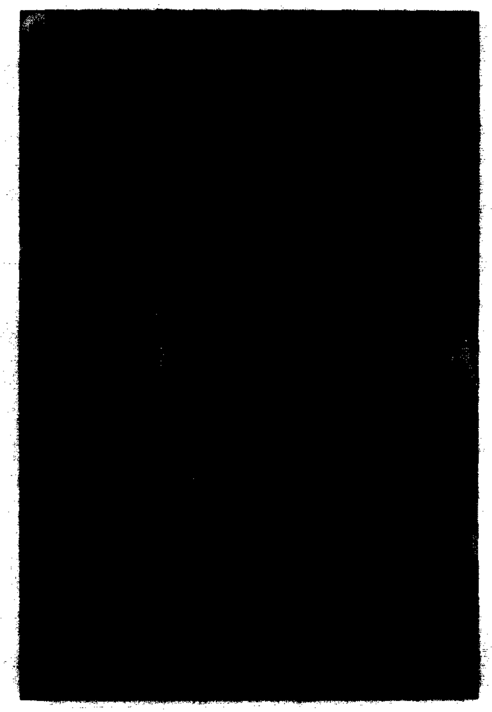


Fig. 5. Plot of thickness vs "length" (diameter of a circle with an area equal to that of unit), showing fields for mafic lavas (*ML*), felsic lavas (*FL*), and low- and high-aspect ratio ash-flow tuffs (*LI* and *HI*) from Walker (1973) and J.A. Wolff and S. Self (unpublished data). Vertical lines indicate estimated average thickness (base) and maximum thickness (top). The Bracks Rhyolite (*Br*) has a much higher aspect ratio than that of the Buckshot Ignimbrite (*Bu*), an ash-flow tuff that occurs in the same area.

developed near the base (Fig. 6B), are absent or obscure through most of the flow, but become progressively more apparent near the top (Figs. 4, 6C, 6D). The bands are horizontal except in a thin upper part where they dip steeply and are locally highly folded (Fig. 6C). The proportion of horizontally laminated versus folded parts of the flow is much greater than that in most small silicic lavas (Christiansen and Lipman, 1966; Fink, 1983). Two scales of columnar joints are developed. Larger columns, 1 – 1.2 m wide, formed initially; smaller columns, 40 – 60 cm wide, formed within the larger columns. The columns show incremental growths bands (DeGraff and Aydin, 1987) that demonstrate that cooling progresses into the flow both from the base and top.



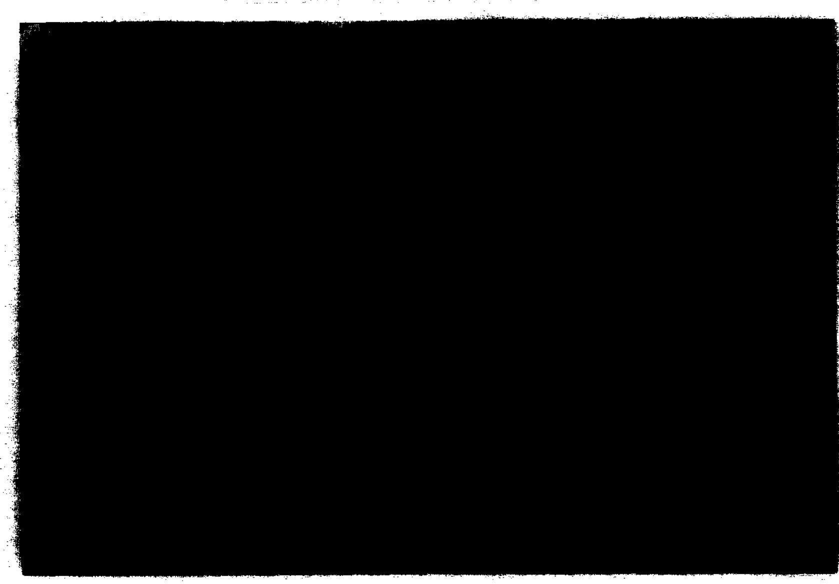


Fig. 6. (A) Typical section in main part of flow, showing massive interior with columnar joints. (B) Basal breccia (approximately 80 cm thick) showing angular to rounded clasts in fragmented matrix overlain by strongly flow banded rock. (C) Flow folds in upper part of flow. (D) Flow folded and vesicular Bracks in upper part of flow; thick, coarsely vesicular bands alternate with thin, nonvesicular bands.

The upper part of the Bracks is an eroded, low-relief surface in which primary features are only locally preserved. Pressure ridges or ogives with amplitudes of a few meters and wavelengths of approximately 10 m occur along the western flank, where they indicate flow to the west and southwest. Upper breccia, lithologically similar to basal breccia, is sparsely preserved as scattered patches that suggest it was initially more continuous. However, part of the upper surface of the Bracks is unbrecciated and consists of smooth, irregular folds with amplitudes and wavelengths of several meters (Fig. 6C). These are much larger than, but possibly analogous to, pahoehoe structures on basaltic lavas. Thin layers (a few centimeters) of aphyric air-fall tuff, mineralogically unlike and clearly unrelated to the Bracks, rest with sharp contact on the folds and were folded along with the upper surface. Thus the upper surface must not have been brecciated, and the tuff must have been deposited before flow ceased. This smooth surface must have had sufficient strength to support the thin tuff but was also sufficiently plastic to flow without brecciating.

Internal textural variations match many of the zones recognized by Manley and Fink (1987) for silicic lavas in general. More than 90% of the Bracks is dense, lithoidal rhyolite (RHY of Manley and Fink). Vitrophyre is rare, other than in some distinctive domes discussed below. Basal vitrophyre is found in only a few locations, all within 10 km of the inferred source. No upper vitrophyre has been found in place, but clasts in basal breccia that show perlitic cracks indicate the former presence of vitrophyre probably derived from the upper part of the flow. Vesicles occur in a few, thin zones (generally about 10 cm thick) near the base and in thicker, more abundant zones in the upper part of the massive interior (Fig. 6D). The vesicular zones and vesicle elongation parallel and largely define flow bands (Fig. 6D); they may have formed as a result of shearing-induced thermal feedback and local reduction of water solubility as suggested by Nelson (1981). These zones are all coarsely vesicular (Fig. 6D) and broadly equivalent to the CVP (coarsely vesicular pumice) of Manley and Fink. Vesicles are elongate tubes or pumpkinseeds, approximately 1 mm to a few centimeters long, and one-tenth or less that thick. Maximum porosity is about 15%. A few, less elongate megavesicles up to 50 cm in diameter occur scattered through the flow.

More finely vesicular material, similar to FVP (finely vesicular pumice) of Manley and Fink, has been found only as clasts in breccia but presumably formed in the uppermost, now eroded part of the flow. Vesicles range from 0.05 mm to several millimeters long. The smallest vesicles have highly irregular, contorted shapes; larger vesicles are mostly more regular and round. Porosity in this more finely vesicular material reaches about 25%. None of this vesicular material resembles pumice of pyroclastic flows. Porosity is much lower than that in pyroclastic pumice, and vesicles walls are thicker than the vesicles.

The sparsity of vitrophyre and of finely vesicular pumice may reflect differences in size and composition between the thick, peralkaline, low-silica (68–69% SiO_2) and probably volatile-poor Bracks and smaller, more silicic and volatile-rich lavas described by Manley and Fink (1987). The Bracks magma probably had significantly lower viscosity than that of high-

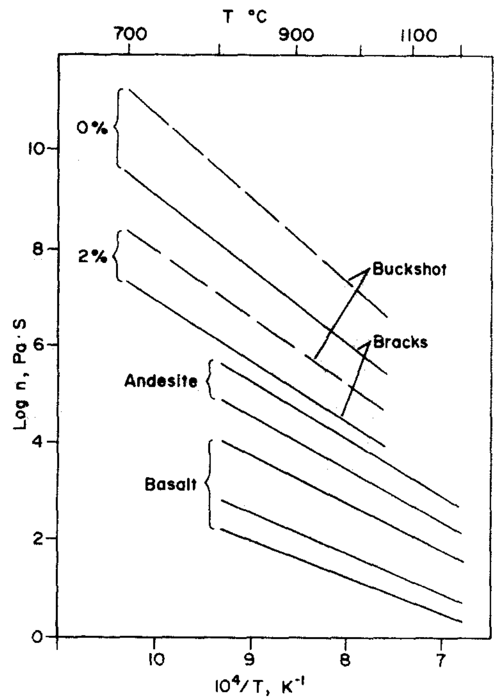


Fig. 7. Calculated Newtonian viscosities of Bracks Rhyolite (solid lines), Buckshot Ignimbrite (dashed lines), and typical andesites and basalts (Carmichael et al., 1974) as functions of temperature. Viscosities are calculated from whole-rock compositions by the method of Shaw (1972) and are intended for comparison only. Viscosities of Bracks and Buckshot are calculated with 0% and 2% assumed H_2O + fluorine contents. Original volatile content of Bracks was probably low, and degassing during eruption would ensure a low water content during flow along the surface. At inferred 900°C minimum eruption temperature, viscosity of Bracks flow would have been approximately 10^7 Pa s. In contrast, typical low-temperature (700°C), hydrous rhyolite would degas during eruption and have a viscosity around 10^{11} Pa s.

silica rhyolite (Fig. 7). The lower viscosity would enhance crystallization such that only the most rapidly cooled parts would remain glassy. Prolonged heating of the ground and basal breccia by the extensive flow would allow relatively slow cooling of the base; basal vitrophyre would be less likely to form. Lower volatile contents would reduce total vesiculation, and lower viscosity would allow bubbles to coalesce, thus minimizing the amount of finely vesicular material.

Domes

Numerous vitrophyric domes intrude the Bracks in the central part of its outcrop, generally within areas where it is more than about 80 m thick. They are most thoroughly studied and appear to be most abundant in a 7-km-long belt in the north-central part of the outcrop (Fig. 8). All domes are chemically and mineralogically identical to the rest of the Bracks. They differ only in being glassy, whereas the rest of the Bracks is almost entirely crystalline. The domes are discussed briefly here and in more detail by Laubach and Henry (in prep.).

Within the area most intensely studied (Fig. 8), we recognize two end members of domes on the basis of dome and host-rock geometry. The more abundant type comprises all domes in the southern 6 km of Figure 8. These are circular in plan view and have smooth, regular cross sections (Fig. 9). Dips of contacts with crystalline parts of the Bracks range from about 15° to nearly vertical. These domes intrude at least to the preserved upper surface of the Bracks, just below what must have been upper breccia. Thus, they may have breached the top of the Bracks during emplacement. These domes occur in crude north-northwest-striking groups. Both domes and crystalline Bracks are cut by similarly oriented joints that may be analogous to the surface fractures associated with vents for silicic domes in Medicine Lake Highland, California (Fink and Pollard, 1983). Devitrification of a few domes along joints indicates that the joints formed during initial cooling rather than during some much later event.

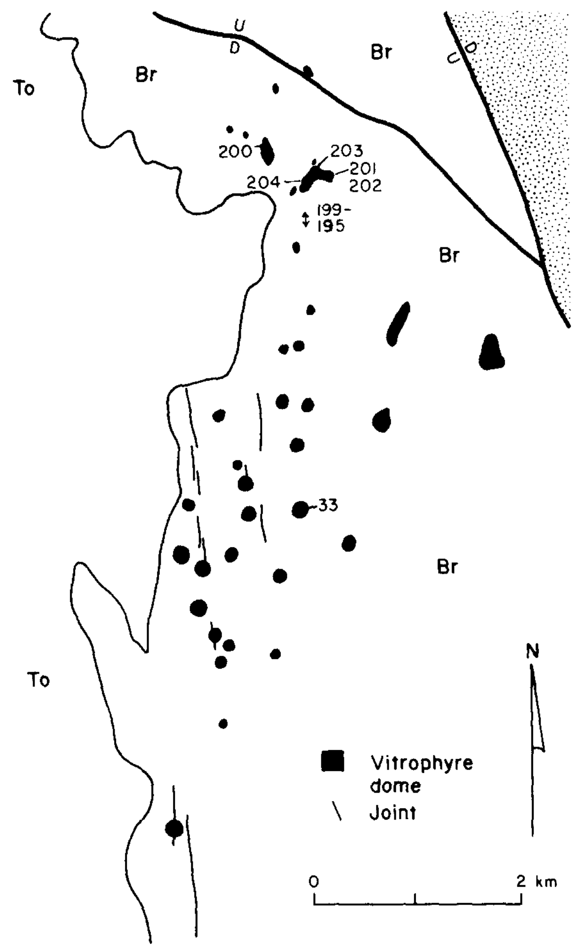


Fig. 8. Map of vitrophyric domes and associated joints (see Fig. 2 for location). Most domes are circular in map view and have regular, rounded cross sections (Fig. 9). Northernmost domes are amoeboid to elongate. North-northwest-striking joints may overlie a fissure vent system that fed the Bracks lava flow. *To* = older volcanic rocks; stipple = Upper Cenozoic basin fill. Numbers indicate locations of analyzed samples from Table 1.

More irregularly shaped domes occur in an approximately 1 km² area in the north part of Figure 8; the less thoroughly studied domes south of Figure 8 all seem to be of this type. Domes range from highly irregular, amoeboid bodies up to 300 m in longest dimension to thin fingers as little as 10 m in diameter and at least

Fig. 9. Typical regular-shaped dome, approximately 125 m in diameter. Columns in dome plunge radially inward, approximately perpendicular to contact with crystalline rock. Columns in crystalline rock at contact are also perpendicular to contact but hinge to more nearly vertical toward the top of the flow.

25 m high (Fig. 8). Margins of individual domes range from vertical to as low as 15°. Crystalline Bracks in the area of irregular domes is complexly and irregularly folded. Fold shapes include both symmetric and asymmetric anticlines and synclines, steep domes, and radially inward-dipping bowls. The antiforms are probably underlain by vitrophyric domes; the synforms indicate withdrawal of material from below. In a few locations, irregular domes overlie thin bands of crystalline Bracks at the base of the flow.

Several features demonstrate that what is now vitrohyre intruded the rest of the Bracks while both were liquid. Flow bands in both types of domes parallel contacts. Most crystalline Bracks deformed plastically in response to the intrusions. Locally, small areas of crystalline Bracks are brecciated at contacts, indicating more brittle behavior. Groundmass of the brecciated material is so finely crystalline that individual grains cannot be distinguished with standard petrographic methods. This texture suggests the rock was glassy or devitrified, and therefore relatively brittle, at the time of intrusion. Columnar joints in both domes and intruded rock are nearly perpendicular to contacts (Fig. 9), indicating they cooled and solidified in response to the contact. Joints near the top of the flow above the flank of a dome are vertical. Inward toward a dome, joints rotate in several abrupt hinges to more nearly orthogonal to the dome margin. Joints within domes plunge radially inward.

We suggest two origins for the domes: (1) rootless intrusion by a lower-density, basal layer of the flow, and (2) emplacement from an underlying fissure system that fed the flow. In the first case, cooling, possibly accompanied by partial groundmass crystallization of the upper part of the flow, would increase its density relative to the lower part. A temperature difference of 200°C between upper and lower layers (700 and 900°C, respectively) would give a density difference of 0.04 g/cm^3, easily enough to initiate diapiric dome growth. Greater groundmass crystallinity of the upper part cannot be demonstrated but would be consistent with lower temperature. The irregular domes surrounded by strongly folded crystalline Bracks are consistent with this mechanism. Basins adjacent to many domes indicate withdrawal of material to balance the upwelling dome. Possibly similar, rootless, dikelike to bulbous bodies of glassy rhyolite intrude upper parts of rhyolite lavas in southwestern Idaho (Bonnichsen and Kauffman, 1987).

In contrast, the regular domes uplift crystalline Bracks but are not accompanied by equivalent withdrawal. This relation suggests that new material was added from below, which could only have been from feeders to the flow. Magma pressure alone is sufficient to cause intrusion and doming, but density contrast similar to the first case could also contribute. Crude alignment of the domes and parallelism with the joints is consistent with eruption along a series of north-northwest-striking fissures. Localization of emplacement in a few domes rather than continuously along fissures is consistent with numerical modeling of dikes (Delaney and Pollard, 1981) and observation of volcanic eruptions (e.g., Richter et al., 1970). Both studies indicate that flow occurs initially along the entire length of a fissure or dike but, with time, is concentrated in discrete sites. Additionally, some withdrawal adjacent to the irregular domes may reflect draining of lava back into fissures (Jackson et al., 1975). Dikes that could mark former fissures have not been found. However, the base of the Bracks below the regular domes is not exposed.

Source

Several features suggest that the Bracks erupted from fissure vents in the north-central part of its outcrop. The Bracks is thickest there, and ramps, pressure ridges, and trains of elongate vesicles indicate flow outward from that area (Fig. 2). Preferential flow to the south from a source in the north-central part of its outcrop is consistent with a depositional surface that dipped gently southward (Walton, 1975) and the thickness pattern (Fig. 2). The cluster of regular vitrophyric domes (Figs. 2 and 8) may mark the source area, consistent with the thickness and flow patterns. North-northwest-striking joints associated with the domes suggest that the Bracks erupted from fissures. Although no dikes of Bracks Rhyolite are exposed, a dike that fed a Star Mountain flow is (Henry et al., 1989). The Bracks may have buried a similar source. Many small rhyolite domes are thought to be fed by dikes, which are nevertheless difficult to recognize (Fink and Pollard, 1983). The uniformity of thickness of the Bracks demonstrates that it did not pond within a caldera anywhere within its outcrop. The eastern part of the Bracks is buried, however, so a source in that area cannot be disproven.

Flow distance from a north-central source to the southernmost outcrops is slightly more than 30 km. If the source is more centrally located or more widely distributed beneath its outcrop, flow distance may be much less. The elongation of Bracks outcrop could indicate an extensive, generally north-trending vent system. Maximum flow distance would be only about 10 km if vents extend the entire length of its main outcrop. However, flow direction indicators (Fig. 2) seem inconsistent with this possibility.

Composition and mineralogy

The Bracks is chemically and mineralogically homogeneous, which supports the field observations that it is a single flow. Thirteen samples representing lateral, vertical, and textural variants were analyzed. All samples contain 68 to 69% SiO_2, expressed H_2O-free (Table 1). By the classification of Le Bas et al. (1986), it is on the boundary between rhyolite and trachydacite. Minor variations in alkalis, CaO, Fe^{2+}/Fe^{3+}, and H_2O reflect ubiquitous hydration, devitrification, or oxidation. Analyses of least altered samples indicate that the Bracks is slightly peralkaline. Homogeneity of the Bracks is best illustrated by the narrow range of rare-earth-element compositions in the samples (Table 1; Fig. 10).

The Bracks contains 10 to 15% phenocrysts,

TABLE 1

Chemical analyses of Bracks Rhyolite

	Vitrophyres from Domes				Crystalline from Main Body of Flow								
	H87-201	H87-203	H87-200	H88-33	H87-202	H87-204	J85-72	J85-76	H87-195	H87-196	H97-197	H97-198	H97-199
SiO_2	67.47	67.09	67.15	67.00	67.06	68.61	69.52	69.12	67.85	68.24	68.03	68.03	68.45
TiO_2	0.54	0.54	0.54	0.53	0.53	0.53	0.54	0.56	0.52	0.53	0.52	0.52	0.52
Al_2O_3	12.61	12.66	12.87	13.14	12.60	13.03	12.58	12.86	13.04	13.06	13.03	13.17	13.05
Fe_2O_3	1.88	2.15	2.89	1.21	4.74	4.32	4.30	4.50	3.89	4.85	5.79	5.23	5.26
FeO	3.65	3.20	2.75	4.37	0.90	1.40	1.68	1.46	1.86	1.21	0.13	0.71	0.68
MnO	0.22	0.20	0.21	0.23	0.13	0.17	0.16	0.22	0.19	0.22	0.08	0.12	0.16
MgO	0.23	0.26	0.20	0.25	0.30	0.40	0.23	0.28	0.20	0.19	0.31	0.34	0.24
CaO	1.50	1.59	1.40	1.55	0.39	1.15	1.16	0.56	0.83	0.82	0.56	0.56	0.57
Na_2O	4.62	4.29	4.16	4.78	4.23	3.89	4.56	4.34	4.72	4.58	4.59	4.58	4.46
K_2O	5.02	4.80	5.43	4.27	5.99	6.81	5.23	5.58	5.46	5.19	5.27	5.34	5.43
P_2O_5	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	0.06	0.06	<0.24	<0.24	<0.24	<0.24	<0.24
CO_2	0.11	0.15	<0.01	0.11	<0.01	0.32	0.22	0.00	<0.01	<0.01	<0.01	<0.01	<0.01
H_2O+	1.99	2.64	2.08	2.24	0.54	0.61	0.48	0.56	0.40	0.64	0.69	0.72	0.56
F				0.08	0.07		0.07	0.10	0.08	0.09	0.06	0.09	0.09
-O for F				−0.03	−0.03		−0.03	−0.04	−0.03	−0.04	−0.03	−0.04	−0.04
Total	99.84	99.57	99.68	99.73	99.26	99.43	100.76	100.16	99.01	99.59	99.03	99.37	99.44
Y	84	84	82	84	84	71	76	80	86	88	82	80	79
La	77	75	77	74	77	68	71	72	79	88	75	76	87
Ce	173	168	166	171	177	152	156	171	166	182	157	162	173
Pr	23	21	24		21		19	20					
Nd	75	73	74	71	74	66	70	71	76	82	69	74	87
Sm	16	16	16		16		14	15					
Eu	2.4	2.4	2.3	2.2	2.5	2.2	2.2	2.4	2.4	2.5	2.4	2.4	2.6
Gd	16	16	16	16	15	15	15	14	16	18	15	16	16
Tb	2.5	2.6	2.5		2.4								
Dy	15	15	15	15	15	14	14	15	15	16	14	15	16
Ho	3.0	2.9	2.9		2.9								
Er	10.1	10.2	9.8	9.9	8.7	8.9	9.1	8.7	10.1	10.4	9.4	9.8	8.9
Tm	1.3	1.3	1.2		1.2								
Yb	9.3	9.4	8.7	9.0	9.1	7.9	7.7	8.9	9.0	8.9	8.6	8.8	8.9
Lu	1.4	1.4	1.3	1.4	1.4	1.2	1.2	1.3	1.4	1.3	1.3	1.3	1.2

Sample locations shown on Figures 2 and 8. Samples H87-201 and H87-203 are vitrophyres from same dome; samples H87-202 and H87-204 are from crystalline rock adjacent to the dome. Samples H87-195 (bottom) through H87-199 (top) represent vertical section through flow. Analyses by ICP-optical spectrometer (major oxides; rare earth elements on some samples) and ICP-mass spectrometer (rare earth elements) by Steven Tweedy and Jonathan Blount, Mineral Studies Laboratory, Bureau of Economic Geology.

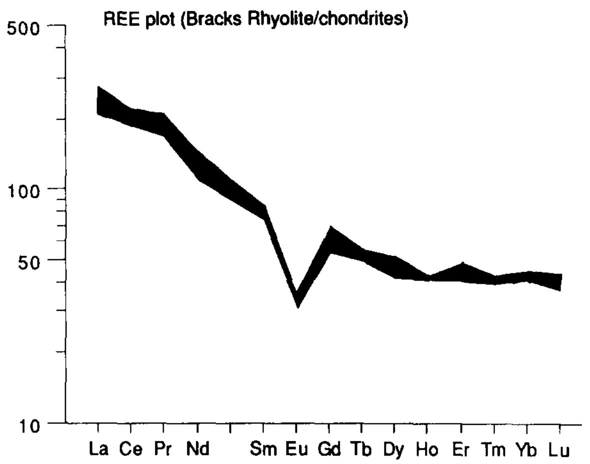


Fig. 10. Chondrite-normalized rare-earth element patterns for thirteen samples of Bracks Rhyolite representing the entire outcrop area. Band encompasses entire range of compositions.

dominantly of alkali feldspar with minor iron-rich clinopyroxene, fayalitic olivine, and magnetite (Fig. 11A). All samples contain the same assemblage in the same proportions. These minerals occur as individual grains and combined in glomerocrysts up to 1.2 cm long. Most phenocrysts are euhedral, but some rounded edges and embayments indicate minor resorption. Alkali feldspars are slightly zoned, from Or_{34} to Or_{40} (Fig. 12). Feldspar phenocrysts from fourteen samples, representing complete spatial and textural variation, show the same narrow range of composition. Clinopyroxene and fayalite show similar narrow compositional ranges for all samples (Fig. 12). Vapor-phase arfvedsonite occurs as equant, 0.1-mm-diameter grains within cavities in the upper part of the flow and supports the chemical data that indicates the Bracks is peralkaline. Groundmass of vitrophyres consists of microlites of alkali feldspar and dendritic to acicular clinopyroxene surrounded by glass (Fig. 11B); this texture indicates rapid crystallization from a homogeneous melt cooled well below its liquidus (G.E. Lofgren, pers. commun., 1989). Twist and French (1983) found similar textures in felsite lavas of the Bushveld Complex, South Africa. Granophyric (Smith, 1960) or micropoikilitic (Lofgren, 1971) texture, in which quartz encloses alkali feldspar laths, is developed in more coarsely crystalline, interior parts of the flow, where it presumably reflects slower cooling. This texture overprints and obscures the microlites in some samples. Spherulitic texture is rare. Phenocrysts are generally aligned, but microlites are not, indicating they crystallized after flow ceased.

Discussion

Evidence for a lava flow origin

Many lines of evidence indicate that the Bracks Rhyolite is an extensive lava and not an unusual pyroclastic flow. The Bracks has all the features of a lava, such as flow bands and folds (Fig. 6), lower and upper breccias (Fig. 6), elongate vesicles, steep, abrupt flow fronts, and flow fronts that break up into individual flow lobes. Except for its great extent, a lava-flow origin probably would not be doubted. Flow bands and folds are common in rheomorphic tuffs (Wolff and Wright, 1981), including several in Texas (Parker, 1986), and upper breccia has been identified in one exceptional case (Henry et al., 1989), but some features of the Bracks are unique to lavas. For example, basal breccia is probably the most diagnostic feature of a lava. Basal breccia, composed of a variety of textural types of Bracks, occurs throughout its extent, is uniformly coarse, and varies markedly in thickness over short lateral distances. The lack of clast size variation demonstrates that it is not some unusual basal lithic accumulation layer of an ash-flow tuff, which would fine away from source. Changes in thickness reflect variations in the amount of material spalling from the front and top of the flow. Local absence of breccia probably represents one end member of this variation. This type of breccia is characteristic of all lavas, not just silicic ones (Manley and Fink, 1987; Cas and Wright, 1987), and indicates that the Bracks flowed as a lava over its entire extent.

Fig. 11. Photomicrographs of Bracks.
(A) Vitrophyre showing euhedral, unbroken alkali feldspar phenocryst with clinopyroxene inclusion and altered fayalite. Note homogeneous groundmass of glass and unoriented microlites. Long dimension approximately 5 mm.
(B) Microlites of alkali feldspar and dendritic to acicular clinopyroxene indicating rapid crystallization from a homogeneous melt. Long dimension approximately 0.2 mm.

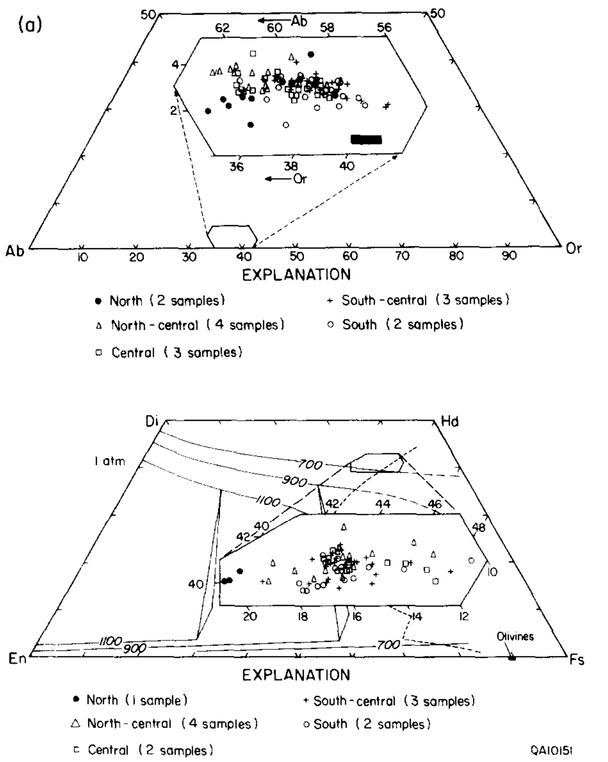


Fig. 12. Compositions of phenocrysts in Bracks Rhyolite; samples represent complete lateral, vertical, and textural variation. Note narrow range of compositions of all phenocrysts.
(a) Alkali feldspars from 14 samples. Bar shows maximum estimated analytical error.
(b) Clinopyroxenes and olivines from 12 samples plotted on pyroxene solvus of Lindsley (1983).

In contrast, comparable basal breccia cannot form from a pyroclastic flow. The quenched base of a pyroclastic flow is likely to best preserve evidence of pyroclastic origin. Conceivably, intense, high-strain-rate rheomorphism could brecciate the quenched, brittle base, generating a deposit composed of ash-flow tuff clasts. This deposit would not resemble a lava-flow breccia. Alternatively, secondary flow of a tuff beyond the limits of the initial pyroclastic flow could generate a lava-flow breccia but only beyond the distal ends of the pyroclastic flow. Not only would the distribution of such a breccia be unlike that of a true lava-flow breccia, but secondary flow is least likely in the thin, distal parts of an ash-flow tuff.

Petrographic and chemical data provide more subtle evidence of a lava-flow origin. The Bracks contains euhedral, unbroken phenocrysts (Fig. 8) and many delicate glomerocrysts that would not have been likely to survive explosive eruption. In contrast, many tuffs contain broken phenocrysts of a wide size range. Groundmass textures, consisting of alkali feldspar microlites and acicular to dendritic pyroxene, in vitrophyre are identical to those found in small, conventional silicic lavas (Swanson et al., 1989). These textures are characteristic of rapid crystallization at high degrees of undercooling and can only form from liquids (Lofgren, 1980; Twist and Elston, 1989; Twist and Lofgren, in prep.). Ash-flow tuff that cooled during eruption as a result of atmospheric mixing (Sparks et al., 1978) is unlikely to have remained at such high temperature and more likely would have devitrified from glass. The Bracks is chemically and mineralogically homogeneous. Almost all tuffs are chemically zoned (Hildreth, 1981). Although the textural and chemical evidence are not definitive, they are more consistent with origin as a lava than as a pyroclastic flow.

Although the source of the Bracks is not certain, a fissure vent such as would feed a lava seems more likely than a caldera. Ash-flow tuffs in Texas having considerably lesser volumes than the Bracks produced well-defined calderas; also, almost all tuffs have been correlated with source calderas (Henry and Price, 1984). The Bracks clearly did not pond within a caldera and apparently had no syneruptive subsidence. Although eruption of any large volume of magma could lead to subsidence, the eruption rate of a lava is probably so much less than that of a tuff that replenishment might be able to keep up with eruption.

The Bracks lacks any features of pyroclastic flows. Despite intense search, we have found no shards, pumice, lithic fragments, or welding zonation. In contrast, the pyroclastic origin of tuffs that have undergone even intense primary or secondary laminar viscous flow is generally easily recognized (Schmincke and Swanson, 1967; Chapin and Lowell, 1979; Wolff and Wright, 1981; Hargrove and Sheridan, 1984). Although secondary flow and recrystallization obscured pyroclastic texture through parts of rheomorphic tuffs, many pyroclastic features, including all those cited above, are locally preserved. Obliteration of groundmass textures would require not just obscuring pyroclastic texture but remelting the matrix, implying substantial input of heat after eruption. We know of no way to accomplish such heating.

Uncertainty about the origin of the Bracks and similar rocks derives from their great extent and low aspect ratio. The extent and aspect ratio of the Bracks are more comparable to those of many high-aspect-ratio-tuffs and unlike typical small silicic lavas and domes (Fig. 5). However, unequivocal ash-flow tuffs in Texas have much greater extents and lower aspect ratios than those of the Bracks (Henry et al., 1988, 1989). For example, the rheomorphic Buckshot Ignimbrite (Henry and Price, 1984) occurs in the same area as the Bracks, has a maximum lateral extent of 85 km, an area of at least 2000 km^2, maximum thickness of only 20 m, minimum thickness in distal areas of less than 2 m, and consequently a much lower aspect ratio (Fig. 5). The Buckshot is considerably more silicic than the Bracks (74% vs 69% SiO_2), and, other factors being equal, should have had a higher magmatic viscosity (Fig. 7). The difference in aspect ratio therefore must reflect differences in eruption and flow mechanisms: the Bracks as lava flow and the Buckshot as pyroclastic flow.

Lack of channelization of the Bracks might also be considered evidence of a pyroclastic origin because most lavas flow within self-generated levees. However, flood basalts, which may be close analogs to extensive silicic lavas, also do not develop channels (Cas and Wright, 1987).

Factors that allow extensive silicic lavas

A continuing problem in the interpretation of the Bracks and other extensive silicic volcanic rocks as lavas is the widely held belief that silicic lavas cannot flow far because of their high viscosity. Thus it is critical to examine the variables that affect the eruption and flow properties of silicic lavas. Several interrelated factors were essential in allowing the Bracks Rhyolite to attain its great areal extent.

(1) High temperature. Temperature of crystallization and eruption of the Bracks can be inferred from three lines of evidence.

(a) Platinum-loop melting experiments at 1 bar along the Ni-NiO buffer indicate liquidus temperatures for the Bracks of 1050° to 1100°C (R. Lange, written commun., 1988). Although these are maximum liquidus temperatures given the nearly anhydrous experimental conditions, the inferred low volatile content of the Bracks suggests that the true liquidus temperature was not much lower. The moderate phenocryst content suggests that eruption occurred at a temperature only slightly below the liquidus.

(b) Although no ilmenite has been found in the Bracks, the closely related Crossen Trachyte and Star Mountain Formation contain magnetite-ilmenite pairs that indicate equilibration temperatures between 900° and 950°C. Temperatures for the Bracks are probably similar; in fact, the lack of a second oxide may indicate the Bracks had not cooled sufficiently for ilmenite to be saturated.

(c) Microlitic to acicular and dendritic textures indicate groundmass crystallization during rapid cooling from near liquidus temperatures (G.E. Lofgren, pers. commun., 1989). Because the groundmass crystallized after eruption and flow, the eruption temperature must have been quite high. The 900°C or greater temperature suggested for phenocryst crystallization is probably also indicative of eruption temperature.

(2) Low water content. The Bracks magma was probably relatively dry as indicated by its anhydrous phenocryst assemblage, lack of precursor pyroclastic deposits, and paucity of vesicles. Additionally, peralkaline magmas

commonly are nearly anhydrous (Bailey and Macdonald, 1987). Low water content is important in minimizing the effect of quenching due to volatile loss during eruption (Westrich et al., 1988; Wolff, 1989). Silicic magmas having initially high water contents generally have low temperatures. During eruption, they degas and are therefore emplaced well below the solidus temperature (Eichelberger et al., 1986; Westrich et al., 1988; Wolff, 1989). Silicic lavas generated in this way would have high viscosities ($\geq 10^{10}$ Pa s) and yield strengths and could not flow far.

(3) Moderately low viscosity. Despite the probable low water contents, the high-temperature, moderate-silica content, and peralkalinity of the Bracks means that it was several orders of magnitude less viscous ($\leq 10^7$ Pa s) than conventional rhyolites (Fig. 7). Lower viscosity is important in increasing flow rate within the eruption conduit (Wilson and Head, 1981) and therefore allowing more rapid eruption. However, the viscosity of the Bracks was still several orders of magnitude greater than that of basaltic flows, so the Bracks did not gain its great extent solely through low viscosity. Lowering of viscosity due to higher water contents does not help because the water would be lost during eruption anyway (Eichelberger et al., 1986). Alternatively, fluorine may play a role in lowering viscosity. Fluorine would not be lost during eruptive degassing because it is preferentially partitioned into the melt (Carmichael et al., 1974). Although analyzed fluorine concentrations are not high (Table 1), they probably reflect minimum magmatic contents because of fluorine loss during hydration or devitrification. Alkalic rocks in Trans-Pecos Texas are commonly enriched in fluorine (Price et al., in press).

(4) Rapid eruption. Eruption rate is thought to be the most important factor in determining length of a lava flow, although most data are from mafic lavas (Walker, 1973). The large volume (> 75 km^3) of the Bracks, probable emplacement from fissure vents, and moderately low viscosity suggest rapid eruption. If the Bracks erupted in 10 years, average eruption rate would have been about 240 m^3/s, a value comparable to that of many basaltic eruptions (Walker, 1973; Swanson et al., 1975). Similar to many large volume basalts, the Bracks may have erupted from a lengthy fissure vent. Actual eruption rate per kilometer of vent was probably much lower.

(5) Slow cooling. Rapid eruption, great thickness, high temperature, and lack of quenching due to water loss allowed the Bracks to cool slowly and remain mobile for a long time. As pointed out by Pieri and Baloga (1986), a high eruption rate really means a flow can travel far before cooling to temperatures at which flow ceases. Glaciers, for which cooling does not constrain flow, can flow for long times and attain extremely low aspect ratios, even though they are much more viscous than silicic magma. Numerical modeling of cooling and crystallization indicates lavas of the dimensions and temperatures of the Bracks could flow for as long as 10 years (Manley, 1989). In 10 years the Bracks could flow 30 km from source at a flow rate of only 8 m/day. Deposition and folding of tuffaceous beds on top of the Bracks suggest protracted flow.

In summary, the Bracks Rhyolite is an unusually widespread silicic lava flow. High temperature, low water content, moderately low viscosity, rapid and prolonged eruption, and slow cooling are essential, interrelated factors that allowed it to attain its wide extent and low aspect ratio. Other silicic lavas having similar properties could also form extensive flows. The characteristics of the Bracks provides a reference with which to evaluate some extensive silicic rocks whose origin has been controversial. Comparison with published descriptions (e.g., Cas, 1978; Twist and French, 1983; Ekren et al., 1984; Bonnichsen and Kauffman, 1987; Milner and Duncan, 1989; Twist et al., 1989) suggests that many of these other rocks are also lavas. Extensive silicic lavas are not only possible, they could be common.

Acknowledgments

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