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An extensive, hot, vapor-charged rhyodacite flow, Baja California, Mexico

Brian P. Hausback
Geology Department
California State University
Sacramento, California 95819

ABSTRACT

The Providencia rhyodacite lava flow of southern Baja California is an unusually extensive salic extrusion. Remnants of the flow overlie lower to middle Miocene volcanic rocks and occur in a 27-km-long belt near the city of La Paz. Isopachs of the flow show a maximum thickness of 120 m and indicate a minimum volume of 8.6 km^3. Persistent flow bands are closely spaced and parallel the base of the flow. These flow bands are thin, planar lithophysal cavities that give the rock a distinct parting. In the upper part of the flow the banding is strongly deformed into isoclinal to open folds. Flow directions, developed from fold axial information, together with the isopach data, suggest that the rhyodacite flowed at least 23 km north-northwest from its source south of La Paz.

The Providencia rhyodacite (68–72.5% SiO_2, 3.8% Na_2O, and 4.5% K_2O) contains about 5% phenocrysts (plag > opx > Fe-Ti oxides) set in a devitrified groundmass of fine-grained alkali feldspar and tridymite ?). Lithophysal planar cavities are lined with large (as long as 3 mm) vapor-phase crystals whose paragenetic relationships define a crystallization order from oldest to youngest: (1) fayalite + thick laths of brown hornblende, (2) α-quartz, (3) hematite, and (4) tridymite + apatite + rare biotite + rare fibrous green hornblende.

Field evidence suggests, but does not prove, that the Providencia rhyodacite is a primary lava flow rather than a remobilized pyroclastic flow. A high volatile content together with a high eruption temperature acted in concert to maintain a low viscosity, a fact that probably facilitated flow of the lava to great distances.

INTRODUCTION

The Providencia rhyodacite flow of southern Baja California, Mexico (Fig. 1) is an important and possibly unique example of what appears to be a siliceous lava that flowed an unusually long distance from its source. Extrusions of rhyolite and rhyodacite typically form steep-sided, short, blocky flows—called coulees—such as the well-preserved Holocene glass flows found in the Medicine Lake Highland and at the Mono and Inyo craters, California. Lavas of these compositions rarely, if ever, flow more than 5 km from their eruptive vents; their morphology and size have been summarized by Walker (1973) and Clough and others (1982). Low fluidity and rapid vesiculation of dissolved gases from siliceous magmas commonly lead to explosive, large-volume eruptions and the resultant generation of ash-flow tuffs. Many voluminous, siliceous, lava-like deposits have been recognized as densely welded ash flows in which secondary mass flowage has occurred. The purpose of this paper is to document the occurrence, flow characteristics, and distinctive vapor-phase mineralogy of this unit and to investigate the possibility of its origin as a volatile-rich ignimbrite.

STRATIGRAPHY

In the La Paz area, the Providencia rhyodacite is the uppermost member of the early to middle Miocene Comondú Formation. This subaerially deposited calc-alkaline volcanic sequence predates the late Miocene to Recent opening of the Gulf of California and consists of silicic ignimbrites, andesitic lahars, and related volcaniclastic sandstones. The source of most of these volcanic units was a chain of volcanoes along the eastern margin of what is now the southern Baja California peninsula. The post-Comondú Late Tertiary rifting of the southern Gulf of California took place along the axis of the previously active Comondú continental volcanic arc (Hausback, 1984a). K-Ar radiometric age determinations on the Comondú Formation in Baja California Sur have yielded an age range of 25–12.5 Ma. The flow is newly named for exposures near Rancho la Divina Providencia near the city of La Paz and is quarried for a well-known resistant building stone. Plagioclase and glass separates from the Providencia lava from 3 widely separated exposures yield K-Ar ages of 19.1 ±1.2 Ma, 19.2 ±0.5 Ma, and 19.7 ±0.2 Ma. (Hausback, 1984a).

FIELD CHARACTERISTICS

The Providencia rhyodacite flow is a prominent mesa-capping unit exposed in a series of hills extending 27 km to the north and south of La Paz (Hausback, 1983). It is a medium-gray, resistant, dense, strongly flow-banded rock. Lack of internal contacts in all exposed sections suggests that the lava is a single flow unit. Identical field characteristics and stratigraphic position, as well as similar compositions (Table 1) and radiometric ages between the various isolated outcrops verify that they constitute a single flow.

The Providencia-flow-capped hills are generally flat-topped, but no original lava surface features such as levees or ogives were recognized; lack of these features suggests that the upper portion of the flow has been eroded. Measured stratigraphic sections were used to construct an isopach map (Fig. 2) from which a minimal preerosional volume of 8.6 km^3 was calculated. The unit is extremely resistant and overlies a 110-m-thick section of friable volcaniclastic sandstone and tuff (Fig. 3). Erosion of these less-competent units necessarily undermines the Providencia layer and leaves it as isolated cap rocks. The regular thickness decrease to the north and the flat-topped morphology of the outcrops also suggests that the flow remnants are eroded down to a natural stratigraphic zonal break. Of the original areal coverage, estimated at about 200 km^2, only 6% remains today.

The base of the flow shows only minor local relief, so that the unit was probably emplaced on a topographically smooth substrate. The isopachs indicate a maximum thickness of about 120 m toward the southern end of the flow exposures; this suggests that this area, known as Cerro San Ramon, is the site of the main eruptive vent for the flow. Therefore, the flow moved at least 23 km (of its 27 km extent) to the north from its source. The stratigraphy has been faulted and warped since deposition, so that the northernmost, distal exposure of the Prodivencia is now 250 m in elevation above its source area, 23 km to the south.

The base of the flow is rarely exposed due to large talus accumulations on the flanks of the mesas. However, on the east side of Cerro Calavera the flow is in sharp contact with an underlying, poorly exposed, thin, red-brown (baked?) ash-flow tuff. No tephra associated with the Providencia flow have been recognized along its base. The lower 5 m of the Providencia flow is a poorly sorted autobreccia that consists of angular boulders of black obsidian. The obsidian is generally massive and locally spherulitically devitrified. It is locally interlaminated with septa of pervasively devitrified laminated rock similar to the bulk flow above. Some obsidian blocks are highly vesicular. This obsidian zone almost surely represents the accumulation of blocks that fell from the advancing flow front, and the zone was subsequently covered by the flow itself.

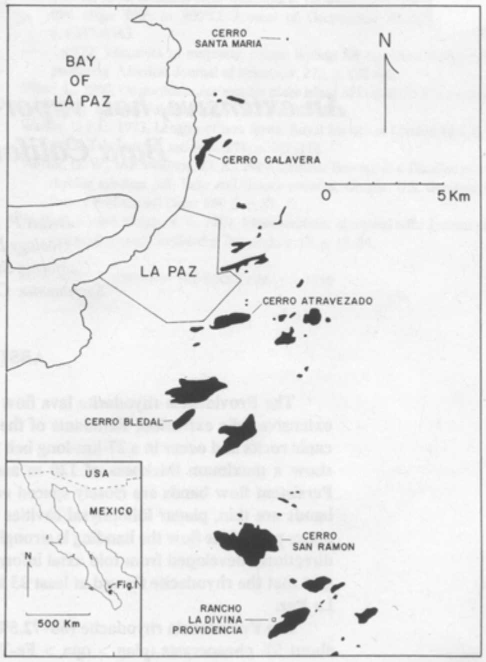

Figure 1. Index map of the La Paz area, southern Baja California, Mexico. Shaded areas indicate the distribution of the Providencia rhyodacite.

The most striking feature of the Providencia rhyodacite is a uniquitous banding defined by thin (as much as 3 mm) white to light-gray laminations set in a medium-gray to brown groundmass (Fig. 4). Vapor-phase minerals wholly or partially encrust these planar laminations. The bands are laterally continuous (over several meters), planar lithophysal laminations that roughly parallel the base of the flow and are irregularly spaced from 2 to 10 mm apart. They are strongly deformed into isoclinal folds at the base of the lava and have horizontal axial planes. Toward the

TABLE 1. PROVIDENCIA RHYODACITE CHEMICAL ANALYSES

Specimen Wt %	433 (1)	432 dark (2)	432 light (2)	113M (2)	3 (2)	44 (2)	239 (2)	248 (2)	383 (3)	249 (3)	240 (3)	XRF ave. σ	383 (4)	383 (5)
SiO_2	62.11	61.07	68.83	70.96	72.57	73.48	72.58	72.47	67.93	69.07	69.89	1.00	0.06	0
TiO_2	1.19	1.21	0.58	0.48	0.47	0.42	0.48	0.47	0.46	0.47	0.48	0.05	18.64	49.23
Al_2O_3	16.28	15.95	13.65	13.48	13.70	13.73	13.62	13.88	12.79	13.10	13.28	0.90	1.42	0.03
FeO*	5.94	6.12	3.09	2.59	2.61	2.31	2.55	2.63	2.56	2.50	2.66	0.20	75.46	47.92
MnO	0.13	0.08	0.03	0.05	0.06	0.06	0.05	0.05	0.07	0.07	0.07	0.02	0.65	0.95
MgO	0.73	0.70	0.26	0.08	0.08	0.08	0.11	0.12	0.08	0.10	0.17	0.20	1.26	1.88
CaO	4.65	4.65	1.46	1.10	1.01	0.96	1.12	1.21	1.32	1.26	1.37	0.15	0	0.01
Na_2O	3.95	4.08	3.83	3.77	3.87	3.96	3.82	4.03	3.49	3.92	4.26	0.30	----	----
K_2O	3.12	2.83	4.39	4.58	4.58	4.92	4.56	4.74	4.61	4.59	4.10	0.50	----	----
V_2O_5	----	----	----	----	----	----	----	----	----	----	----	----	0.17	0
Cl (ppm)	38	49	39	38	96	72	88	148	717	560	693		----	----
Ba (ppm)	1061	1160	1651	1653	1502	1453	1558	1364	1361	1427	1537		----	----
L.O.I.	----	----	----	----	----	----	----	----	3.86	----	----		----	----
Total	98.21	96.81	96.30	97.24	99.12	100.07	99.06	99.75	97.38	95.27	96.50		97.66	100.02

(1) Intermingled andesite
(2) bulk rhyodacite
(3) basal obsidian
(4) magnetite-ulvospinel
(5) ilmenite-hematite

Analyses 1, 2, and 3 from XRF.
Analyses 4 and 5 from electron microscope.

*Total iron reported as FeO.

L.O.I. = Loss on ignition.

top of the exposures, these folds become progressively more open, less inclined, and attain amplitudes of up to 5 m.

Closely spaced minute parasitic folds with amplitudes up to 3 mm are superimposed on the larger folds throughout the upper parts of the flow. The axes of the parasitic folds are nearly always parallel to the axes of the larger folds. Locally, however, these subordinate structures are refolded by their larger hosts. Figure 2 shows stereographic plots of the average orientations of fold axes from several outcrops throughout the La Paz area. The fold axes in any one outcrop area show a wide scatter in orientation (Fig. 5), as would be expected for deformational features of this type formed by internal body forces within a viscous flowing medium.

After each fold was formed, it was subjected to rotation in the direction of continued shear, as are all linear structural elements in a flow. Nonetheless, the fold axes are not randomly oriented, and the mean orientation of the fold axes is the best available estimate of the original attitude of the folds. The average fold axis in any one area is subhorizontal with a trend consistently perpendicular to the northerly flow direction, as shown in Figure 2. This results from a process which is analogous to a carpet sliding down a ramp, folding and rolling over itself under its own weight, the fold axes developing perpendicular to the direction of movement. Fold vergence and rolling directions of andesitic magma blebs within the flow (Fig. 6) give the sense of movement to otherwise dipolar flow directions derived from the mean fold axes. The average orientations of the flow folds, together with the isopach data, indicate that the flow moved almost due north from its source at Cerro San Ramon.

PETROLOGY

The Providencia flow is a medium-gray, phenocryst-poor rhyodacite. The groundmass is generally nonvesicular and devitrified to alkali feldspars, mainly sanidine, and some form of very fine-grained silica, probably tridymite, based on X-ray powder diffraction and electron microprobe analyses. An exception to this is the black, vesicular, microlitic obsidian found only in a boulder breccia along the base of the flow in all known exposures.

The flow contains about 5% phenocrysts: plagioclase (An = 30–42% with oscillatory to slightly reversed zoning) > hypersthene > Fe-Ti oxides. The assemblage is relatively homogeneous throughout the flow. At the suspected source area, however, the flow is composed of a mixed lithology; the typical gray phenocryst-poor rhyodacite is intermingled with formless blebs and elongate swirled septa of dark-brown andesite (Fig. 7) that contains 12% phenocrysts of a similar assemblage, but with augite instead of hypersthene. Contacts between the two lithologies are marked by lithophysal laminations. Neither lithology appears quenched or in any way affected along the contacts. The andesite was probably liquid when it was incorporated into the rhyodacite, unlike other scarce, accidental, angular clasts of andesite in the flow.

XRF whole-rock analyses (Table 1) show that the lava flow is a metaluminous, alkaline rhyodacite to rhyolite. The compositions of the bulk flow and the basal obsidian determined from numerous samples along the length of the flow show almost no significant variation, with the exception of SiO_2. SiO_2 ranges

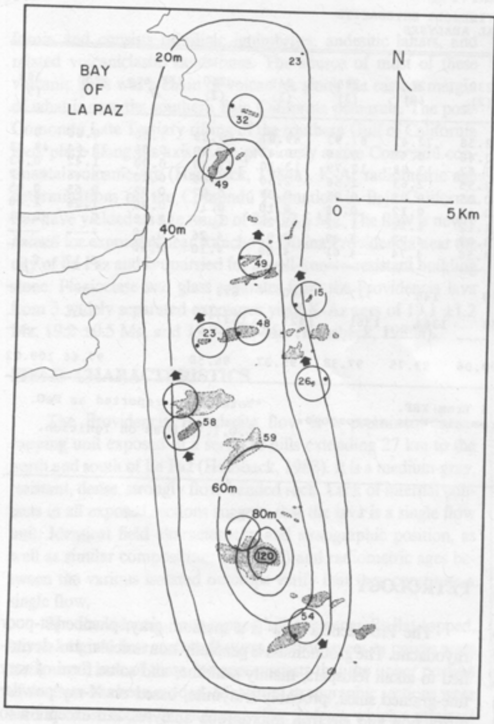

Figure 2. Isopach reconstruction map and flow-fold information. A flow volume of 8.6 km^3 is calculated within the 20-m isopach. Small numbers are the flow thickness in meters. Circles are lower hemisphere, equal-area, oriented stereograms; dots within circles indicate the average fold-axis orientation; they yield a nonunique flow direction perpendicular to the fold axis. The arrows show the inferred sense of flow (determined from fold vergence and rolling of andesitic magma blebs).

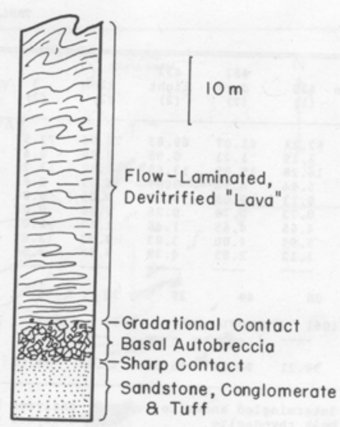

Figure 3. Composite stratigraphic section of the Providencia rhyodacite.

from 68–72.5%, a variation that may result from magmatic differentiation prior to eruption or from the remobilization and redistribution of SiO_2 during posteruptive vapor escape. The andesite lithology at the source area represents a mafic liquid that either intruded into the base of the magma chamber, an event which may have caused the eruption of the Providencia lava, or was a coexisting phase of magma that intermingled and erupted with the last-erupted rhyodacite.

Fe-Ti oxide geothermometry (Buddington and Lindsley, 1964; Carmichael, 1967; Ghiorso and Carmichael, 1981) indicates an eruptive temperature of 912 °C and an oxygen fugacity of $10^{-12.2}$, on the basis of microprobe analyses of fresh, unexsolved Fe-Ti oxide crystals from the quenched basal obsidian (Table 1). Eruption temperatures for continental rhyolites and rhyodacites have an approximate range of 790–925 °C (Carmichael and others, 1974), implying that the Providencia rhyodacite was relatively hot when erupted.

VAPOR-PHASE CRYSTALLIZATION

The planar lithophysal partings, so characteristic of the flow, are incompletely filled by a remarkable and diverse suite of vapor-precipitated euhedral crystals (up to 3 mm in size). This mineralization, although commonly overlooked in volcanic rocks, is of great importance in understanding the large volcanic vapor component and its effect on flow rheology. These vapors, except where incorporated into these minerals, are forever lost. The minerals are found throughout the flow, both laterally and vertically through most sections. The vapor phase minerals comprise 1–5% of the total volume of the Providencia flow. These euhedral crystals have precipitated as radiating clusters on the walls of the planar cavities and normally fill the openings.

Eight different mineral phases have been identified in the lithophysae by optical, X-ray diffraction, and electron-microprobe analyses. Paragenetic relationships define a crystallization sequence from oldest to youngest: (1) fayalite + thick laths of brown hornblende (with 3.2% F, 0.25% Cl, and probably containing H_2O); (2) α-quartz; (3) acicular hematite; and (4) tridymite + apatite (with 5% F and probably containing CO_2) + rare biotite + rare fibrous green hornblende (Hausback, 1984b). This unusual suite of vapor-phase minerals is the subject of a separate topical study (Hausback, in prep.).

Figure 4. Typical outcrop of the Providencia rhyodacite displays dense, resistant lava with closely spaced subhorizontal lithophysal laminations. Inclusions near the hammer head are intermingled andesite. Hammer head is 20 cm long.

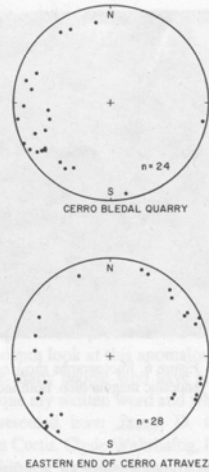

Figure 5. Fold axis orientations from two localities of the Providencia rhyodacite, plotted on lower hemisphere equal-area stereonets.

The planar lithophysal cavities in which this entire crystal suite is developed are laterally continuous over several meters and wrap around magmatic phenocrysts without breaking them. This fact suggests that movement along these bands occurred while the flow was still molten or in a plastic state. As such, the bands were probably shear planes active in the last stages of laminar flow in the cooling mass. Within the laminations, the vapor phase crystals also show no breakage, strongly indicating that they developed *after* all movement along the flow shears ceased. The ubiquitous postemplacement vapor-phase mineralization found in the Providencia flow strongly suggests that an enormous amount of vapor was dissolved in the magma and was, at least partially, retained in solution until the flow settled. The compositions of the vapor-phase crystals show that the lost volatiles of the voluminous volcanic vapor included H_2O, CO_2, F_2, and Cl_2.

Water and CO_2 are the most abundant volatile components commonly found in magmatic vapors (Burnham, 1979), and there is no reason to believe that the vapors associated with the Providencia rhyodacite flow were dissimilar. Primary hydrous phenocrysts such as biotite or hornblende would be expected in a volcanic rock of this composition, but there are none. This can be explained by the calculated high eruptive temperature, which precludes hydrous phenocryst stability, according to the experimental results of Maaloe and Wyllie (1975) and Naney (1983).

SUMMARY AND DISCUSSION

The Providencia rhyodacite is a remarkably long (at least 23 km) silicic volcanic flow that appears to be a lava. The exact original morphology of the flow cannot be accurately reconstructed due to extensive lateral and unconstrained vertical erosional removal since its emplacement in the early to middle Miocene. However, a reasonable reconstruction of this flow (Fig. 2) shows that it is far greater in length than other commonly known siliceous lavas.

The length of a lava flow is controlled by numerous factors, including lava viscosity, total erupted volume, rate of effusion, and morphology and slope of the underlying surface. Walker (1973) suggested that the length of a lava flow is most dependent on eruption rate and viscosity. Malin (1980), on the other hand, suggested that length depends most directly on the total volume of lava erupted. Unfortunately, these studies concentrated on mafic lavas. Very few silicic lavas have ever been observed in eruption, hence in situ viscosity and rates of eruption for salic lavas are essentially unknown.

The calculated Providencia flow volume of 8.6 km^3 or more is large in comparison to most salic lavas. Glass Mountain, probably the largest, best-known Quaternary rhyolite lava, is about 1 km^3 in volume (Eichelberger, 1981) and flowed 2.5 km down steep topography from its vent. However, much larger silicic lavas exist. The Chao dacite flow in northern Chile is 24 km^3 (Guest and Sänchez, 1969) and flowed 12 km from its vent. It is quite clear from their well-preserved surface morphology that young flows like these are primary lavas. However, old and poorly preserved flows such as the Providencia rhyodacite have less obvious interpretations; they possibly originated as either primary lavas or remobilized pyroclastic flows. Both of these eruptive styles commonly give rise to flow-banded rhyolitic extrusions.

Figure 6. Photographs showing (a) fold vergence (example from a loose block) and (b) rolling of an andesitic magma bleb. Both indicate flow to the left.

Field evidence argues against an ash-flow origin for the Providencia rhyodacite and suggests that it is actually a primary lava. There is no evidence for an explosive eruption that commonly gives rise to pyroclastic flows. No basal tephra unit has been found associated with the Providencia flow. In addition, the scarcity of accidental rock fragments in the flow, a typically abundant constituent of ash-flow tuffs, argues against an explosive pyroclastic origin (R. L. Smith, 1985, personal commun.). Furthermore, pyroclastic textures on the microscopic and megascopic scales are completely absent from the Providencia flow, whereas rheoignimbrites reported in the literature (Wolff and Wright, 1981; Chapin and Lowell, 1979; Deal, 1973; Parker, 1972; Lock, 1972; Villari, 1969; Noble, 1968; Walker and Swanson, 1968; Schmincke and Swanson, 1967) show, at least locally, remnant pyroclastic textures.

There is no doubt that the Providencia rhyodacite last flowed as a lava. Vesicular obsidian blocks in the basal zone show that it was a bubbling liquid mass. The foliation, folding, and vertical zonation of the lava are nearly indistinguishable from other well-documented salic lava flows, such as the flow described by Christiansen and Lipman (1966).

Viscosity indirectly controls the length of lava flows (Walker, 1973). The viscosity of the Providencia rhyodacite can be calculated by the method of Shaw (1972). By using this technique, the anhydrous viscosity of the Providencia lava is determined to be 10^8 Pascal-seconds (10^9 poise), assuming the derived eruptive temperature of 912°C. This estimate suggests that the Providencia flow, *if it was anhydrous,* was relatively fluid in comparison to less siliceous dacitic lavas that have measured viscosities in the range of 10^8–10^{10} Pa-s (10^9–10^{11} poise) (Walker, 1973).

The chemistry and amount of volatiles in solution during the eruption and flow of the Providencia rhyodacite is qualitatively suggested by the voluminous and ubiquitous postemplacement vapor-phase mineralization. The vapor component must have been substantial, and included at least H_2O, CO_2, F_2, and Cl_2.

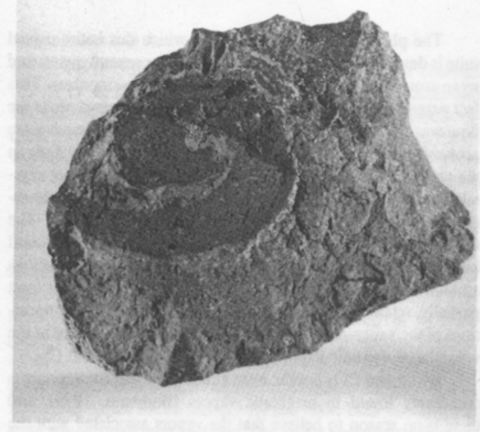

Figure 7. Hand sample of intermingled rock types from the suspected vent-source locality. Swirl is dark andesite within lighter gray rhyodacite. Sample is 12 cm across in the horizontal dimension.

The volatile component of lavas is known to significantly lower silicate fluid viscosity. Shaw (1963) showed that the addition of 7% H_2O to a rhyolitic glass can lower its viscosity by a factor of 10^7. The effects of F_2 are also important in volcanic rocks. F_2 and H_2O have similar effects in lowering silicate melt viscosity. In addition, F_2 has a high melt/fluid partitioning coefficient and will therefore be retained in a magma upon eruption, thereby reducing the explosivity of an eruption and generally maintaining the fluidizing effect of the F_2 in volcanic flows (Dingwell and others, 1985; Rabinovich, 1983).

The original volatile content of the Providencia lava is difficult to estimate. A glass separate from the obsidian basal breccia yielded a volatile content (retained in the glass at 110 °C) of 3.67 wt.%. If it is assumed that this 3.67% volatile content represents the original $H_2O + F_2$ content, the viscosity was again calculated by Shaw's (1972) method to be 10^4 Pa-s (10^5 poise), a value characteristic of much more fluid lavas such as andesites and basaltic andesites, which commonly *do* flow long distances (Macdonald, 1972; Walker, 1973). Therefore, it is reasonable that the relatively high temperature (912 °C) and a high volatile content combined to maintain a fluid Providencia lava, a quality that probably allowed it to flow such a great distance.

These arguments strongly suggest but do not unequivocally prove, that the Providencia flow was a primary lava. The preservation of a pyroclastic texture can prove a lava's remobilization from an ash flow, but lack of that texture cannot absolutely prove an origin as a primary lava. If a very hot, still-fluid ash flow is remobilized, it may strongly resemble a lava. If the pyroclastic texture becomes obscured through intense welding and laminar flowage, evidence of the primary eruptive character of the flow could be lost, but generally seems to be partially preserved. Indeed, there appears to be debate about the very nature of Rittman's (1958) type example of a rheoignimbrite (Wolff and Wright, 1981)—is it, in fact, a lava or a remobilized ash flow? Unusually extensive lavas such as the Providencia may always be suspected of having begun as ash-flow tuffs.

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