

ORIGIN OF VESICLE TYPES AND DISTRIBUTION PATTERNS IN THE
XITLE PAHOEHOE BASALT, IN MEXICO CITY.

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ABSTRACT

Many vesicle features not previously described occur in the conspicuously vesicular tube-fed pahoehoe basalt from Xitle volcano where it extends into Mexico City. A pervasive foliation, defined by the plane of flattening of small "background" vesicles, has been imprinted as an imbrication in the lava near and oblique to the flow-base and commonly also to the flow-top. Its formation implies that many of the flow-units developed by toothpaste-like extrusion, and its preservation implies that the lava initially possessed or soon acquired a yield strength. An evolutionary model is proposed in which the lava initially had a rather uniform content of 20 to 25% of small (≤ 1 mm diameter) bubbles. In all but the thinnest units pipe bubbles then rose, efficiently scavenged bubbles from the lower and middle flow-interior (growing as they did so) and fed the megavesicles of the middle and upper flow-interior. Closure behind ascending pipe bubbles was opposed by yield strength. Incomplete closure behind larger pipe bubbles generated "inverted-cone" vesicles. Some large bubbles ascended diapirically and expanded laterally by wedge action (to form "side-wedge" vesicles) in a steep rheology gradient just below the surface crust. Their surfaces are locally concordant and locally discordant to the foliation. Other large bubbles expanded isotropically (to form "globular" vesicles) in the near-uniform medium of the flow interior and updomed the the foliation above and around them. The large bubbles that formed the remarkable "belljar" vesicles characteristically cut discordantly across and do not disturb the foliation (except in their wake) and rose by bulk subsidence of lava under belljar fractures. The final dynamic act was the rise of a highly-vesicular segregation fluid through vesicle cylinders and veins, to form floors of segregation vesicles or be injected into horizontal hydraulic fractures as segregation veins near the median plane of the lava. The preservation of megavesicles depended on possession by the lava of an appropriate yield strength.

INTRODUCTION

The Trans-Mexican Volcanic Belt contains several thousands of Quaternary andesitic and basaltic volcanic cones, many of which occur in clusters that define monogenetic volcano fields. One of the youngest and best-defined fields, Chichinautzin, is situated immediately south of Mexico City. This field contains many cones younger than 20,000 years (Martin, 1982), the youngest of which is Xitle with a ^{14}C age of 1400 years (Libby, 1952). Important archeological sites in or under the Xitle lava include the Aztec pyramids of Cuicuilco and settlement of Copilco.

Xitle, the only basaltic volcano in the Chichinautzin field, is a lava shield about 6 km in diameter (Ordonez, 1890) surmounted by a pyroclastic cone. Its lava spread into the Valley of Mexico, including the southern part of Mexico City and the campus of UNAM (Universidad Nacional Autonoma de Mexico). This lava flowfield is a rough and stony area known as the Pedregal de San Angel. Much of the Pedregal has been quarried out or built on, but superb outcrops survive in and close to the UNAM campus (Fig. 1) and provided all the new data. The lava is pahoehoe and is subdivided into flow units that are commonly 4 to 6 m thick.

The Xitle lava has 48.7 to 52.0% SiO_2 (Schmitter, 1953). In the outcrops studied it has a glassy chilled margin up to about 10 mm thick containing an estimated 30 vol% of microphenocrysts of olivine, plagioclase, and clinopyroxene.

Because of its situation, youthfulness and well exposed character, the lava has attracted considerable attention. It was mapped and studied petrographically by Ordonez (1890, 1895), and various structural features were described by Waitz and Wittich (1910), Wittich (1917), Schmitter (1953), Badilla Cruz (1977), and Enciso de la Vega (1979). No systematic study has however been made of the vesicle types or their distribution pattern.

This study contributes to the theme that many features of lava flows may result from possession by the lava of a yield strength, either initially on eruption or acquired during cooling. The theme was introduced by Robson (1967) to explain thickness values of Etnean lava (Walker, 1967) and was developed by Shaw (1969), Hulme (1974, 1976), and Sparks et al. (1977). Field measurements of yield strength were made on Makaopuhi lava lake by Shaw et al. (1968) and on Etnean lava by Pinkerton and Sparks (1978) and others. Preservation of pipe vesicles and the symmetrical distribution of vesicles in some pahoehoe were attributed to an acquired strength by Walker (1987, 1989) and Wilmoth and Walker (1993), and the present study further develops this theme. the

Vesicles are ubiquitous in basaltic lava flows but their scientific study has

been long delayed. Aspects of vesicle distribution patterns were recently studied by McMillan et al (1987), Aubele et al. (1988), and Walker (1989); a vesicle-coalescence model was developed by Sahagian (1985) and Sahagian et al. (1989); and pipe vesicles were re-interpreted by Walker (1987), Philpotts and Lewis (1987), and Godinot (1988). The present study considerably extends the scope of vesicle studies.

VESICLE TYPES AND DISTRIBUTION

The Xitle lava is conspicuously vesicular and contains many megavesicles exceeding 0.1 m across. The following describes the main vesicle types and their distribution. The smaller vesicles are often strongly deformed, and their plane of flattening defines a foliation or their elongation to a spindle shape defines a lineation. The relationship between megavesicles and foliation is also described here since it is regarded as an important factor in determining vesicle origins.

Background vesicles are relatively small vesicles that are invariably present in the Xitle lava as a kind of "background" within which the other vesicle-types occur. They have a well-defined size and abundance distribution (Fig. 2). In the thinnest flow units (<1 m) they comprise about 20 to 25% of the lava-volume and are rather uniformly distributed. They increase in size inward from an average of about 2 mm in the crusts. As the flow unit thickness increases, their distribution becomes more heterogeneous and they constitute an ever smaller proportion of the lava. In the thicker flow units (>2 m) they average about 2 mm in diameterⁱⁿ and constitute about 20 to 25% of the upper crust and somewhat less (about 15%) of the lower crust. They are smallest (<2 mm) and scarcest (<1%) in the lower and middle flow-interior and they are largest (commonly >10 mm) in the upper flow interior.

The background vesicles are commonly deformed and are not spherical. Deformation is strongest and most consistent within the basal 0.5 m, and commonly also occurs within the topmost 0.5 m, of each flow unit (Fig. 3). Deformation has produced a flattening in which the aspect ratio (short axis: long axis) may be 0.3 or less. It has also produced an elongation giving the vesicles the form of a triaxial ellipsoid having orthogonal axes x , y , and z with $z > y > x$. The parallelism of the yz plane of background vesicles defines a foliation, and the parallelism of the z axes defines a lineation in the foliation plane.

Within 0.5 m of the flow-base the foliation dips up-flow, and the lineation plunges up-flow. Within 0.5 m of the flow-top the foliation dips down-flow, and the lineation plunges down-flow. Foliation-dip and lineation-plunge are inclined at up to 20° from the flow-base and flow-top, and tend to asymptote

4

In cross sections of some narrow flow units the foliation is seen to curve around the flow-unit axis in a cylindrical arrangement. A foliation/lineation is also found curving around and over the top of certain megavesicles. Other megavesicles occur which do not show this relationship but instead abruptly truncate any foliation/lineation that may exist.

Side-wedge vesicles are generally the most conspicuous vesicles in Xitle lava and constitute up to about 25% of a well-defined zone extending from about 0.2 to 1.0 to locally as much as 2.5 m below the flow-top. They are tabular in form and have an aspect (height/width) ratio typically of 0.3 to 0.03 (Figs. 3a, 4). The largest exceed 2 m wide and are up to 0.2 m high. Estimated volumes range from about 1 to about 500 liters. They taper toward the sides in wedge-like fashion. Their floor tends to be flatter than their roof, and occasionally it shows ropy flow structures indicating that some lateral flowage occurred after the overlying crust solidified. Strands of stretched lava link the roof and floor, and some have ruptured to produce forms resembling stalactites and stalagmites.

The plane of the side-wedge vesicles is parallel with the flow-top, and in outcrops where the background vesicles have a pervasive foliation oblique to the flow-top the side-wedge vesicles cut discordantly across the foliation plane (Fig. 3). Locally this foliation is disturbed by and deflected parallel with the margins of side-wedge vesicles.

Belljar vesicles (dome vesicles of McMillan et al., 1987) are the most striking megavesicles (Figs. 5, 6) and occur in the flow-interior. They have an upwardly-convex roof shaped like a belljar, and an upwardly-convex floor with a lesser curvature than the roof. In plan view they are either circular or oval-shaped, and the largest exceed 2 m in size. Average dimensions (from 34 measured examples) are : width - 0.49 m; height - 0.27 m; height of void (distance between vesicle roof and floor) - 0.11 m. Estimated volumes are 1 to 100 liters. The lowest part of each vesicle extends down as a peripheral cleft that contains or cuts segregation material.

Belljar vesicles have typically not deformed the background vesicles above them and around their sides, and where a pervasive foliation occurs it is abruptly truncated and not disturbed by them (Fig. 5 b). Belljar vesicles exposed in vertical cross section however have a wake below their floor and especially below their periphery where small vesicles are deformed to produce a weak foliation, ~~and especially below their periphery where small vesicles are deformed to produce a weak foliation.~~ below the periphery (Fig. 6 b). ✓

Pipe vesicles (Du Toit, 1907) occur in the basal part of flow-units. They begin 0.05 to 0.2 m above the base and seldom extend higher than 0.5 m up. They are typically 20 to 30 mm wide and are irregularly spaced, typically at 0.1 m. They are almost

5
invariably inclined and plunge up-flow at 10° to 30° except at their top where they may approach verticality. They characteristically plunge more steeply than, and cut across, the pervasive foliation defined by deformed background vesicles (Fig 3b).

Cylindrical vesicles are vertical cylinders typically 0.05 to 0.1 m wide and are much wider than pipe vesicles (Fig. 7). They occur higher in a flow and may extend up to the median level. Examples seen are less than 1 m long. They have a tapering lower end, and a bulbous upper end (Fig. 7a). Background vesicles are deformed in a narrow zone curving over and foliated parallel to the top of each cylinder (Fig. 7b).

Inverted cone vesicles have a V- or a U-shape in cross section and are typically 0.1 to 0.3 m wide. Each has an inverted-cone roof and floor; the apical angle of the floor is less than that of the roof so that each vesicle widens down toward the apex. All examples noted occur in the lower part of a flow unit, within 0.1 to 1.0 m of the base. Some underlie and are closely related to cylindrical vesicles (Fig. 8).

Vesicle cylinders (Du Toit, 1907) are more or less vertical cylinders of highly vesicular rock, typically about 0.05 m wide, that occur in the weakly vesicular lava of the lower flow-interior. They pass into and are evidently closely related to pipe vesicles, but tend to occur higher and may extend up to about the median level. Some pass upward into cylindrical vesicles.

Generally they consist of segregated material and have a porosity of about 50%. Their vesicles tend to be irregular in form and about 5 to 10 mm in size. Many pass into and terminate upward in segregation veins.

Globular vesicles occur in the flow-unit interior. They have a bulbous, tending toward a spherical, shape and measure 0.1 to 0.3 m across. Background vesicles are deformed near them and have a local foliation that curves over the top of each globular vesicle (Fig. 9a). Figure 9b illustrates two globular vesicles, the upper of which has a form suggestive of its strong deformation over the top of the lower, and Fig. 7b illustrates a globular top to a cylindrical vesicle.

Segregation vesicles (Smith, 1967) commonly exceed 0.1 m in size and are floored by highly vesicular segregation material similar to that of vesicle cylinders and segregation veins (Fig. 10). They occur in a well-defined zone generally less than 1 m thick under the side-wedge vesicle zone in the upper flow-interior. Some taper toward the sides like side-wedge vesicles, and others are more akin to globular vesicles. In all, the floor is horizontal.

Segregation veins are approximately horizontal or occasionally vertical narrow sheets up to 0.05 m wide, consisting of highly vesicular segregated material typically with a porosity of near 50%, that cut across the normal basalt. They closely resemble the material of, and are often visibly joined to, vesicle cylinders (Fig. 10(c)).

Individual veins up to 0.05 m thick can be traced laterally for tens of meters. They are in sharp but unchilled contact against normal basalt, and occupy rifts that have the characteristics of tensional fractures (Fig. 10 c). The vesicles they contain tend to be irregular or vermiform in shape and range up to 10 mm in size. They include narrow (about 5 mm) and short pipe vesicles.

INTERPRETATION

Origin of foliation and lineation

Consider the imbrication, the pervasive foliation and lineation that consistently occurs at and near and oblique to the flow-base. Lava flowing freely and laminae over the ground will have a velocity profile as shown by Fig. 11(a) or (b), according to whether it is Newtonian or Binghamian in rheology. The dashed curves trace successive positions of an imaginary and initially-vertical line across the lava. This line is progressively more strongly stretched as flow proceeds, and initially-spherical bubbles in the lava will be deformed and stretched parallel with it. These diagrams are two-dimensional representations of three-dimensional lava in which deformation in general produces bubbles that are not only flattened but are also elongated along an axis.

Consider now the oblique pervasive foliation that occurs at the top of some flow units. An additional feature, namely, extrusion through an orifice from a lava tube is required to explain it. Lava flowing freely and laminae from an orifice will have a velocity profile as shown by Fig. 11 (c) and (d); at the point where it emerges, drag occurs against the roof as well as the floor of the orifice and this causes the profile to be symmetrical about the median level at this point. Bubbles at the flow-top are thus deformed where the lava emerges from the orifice but may suffer no significant subsequent deformation, whereas bubbles at the flow-base may continue to be strongly deformed as flow proceeds.

The deformation in the uppermost roughly 0.5 m is evidence that the flow-units that show it emerged as toothpaste lava from lava tubes. Fine examples of drained-out lava tubes 5-8 m wide by 2-3 m high are seen at several places in the Xitle lava.

Surface tension and gas pressure in bubbles oppose deformation forces and tend to re-instate a spherical bubble shape. The fact that background vesicles preserve their strongly deformed shape in the top and bottom half-meter of

flow-units is additional evidence that the Xitle lava possessed a yield strength, as is suggested by the following simple observations.

Typical Hawaiian pahoehoe initially has a negligible yield strength and a viscosity of about 10^3 Pa s, indicated by the extent to which mafic crystals have settled (Rowland and Walker, 1989). Strongly deformed vesicles occur only in the outermost layer 10–20 mm thick of crust. A crust this thick takes 1 to 15 mins to form (Wilmoth and Walker, 1993). Vesicles inside that outermost layer are approximately spherical. If, as is likely, they had been deformed by flow, then a relaxation to reinstate a near-spherical bubble shape would thus have taken a minimum of about 15 mins.

The pahoehoe of Xitle evidently had a significantly higher viscosity since it consists of significantly larger flow-units having a rougher surface texture, and vesicles that are much more commonly deformed. In these respects it resembles toothpaste lava and rough pahoehoe in Hawaii which, from mafic-crystal distributions, had an effective viscosity of about 10^4 Pa s (Rowland and Walker, 1989) or ten times greater than for normal Hawaiian pahoehoe.

If the viscosity of Xitle lava was about 10^4 Pa s, then surface tension and gas pressure should have been capable of reinstating a spherical vesicle shape in about ten times longer than in normal Hawaiian pahoehoe, namely a minimum of 150 mins. Strongly deformed bubbles however occur in a crust at least 0.5 m thick, which would take as long as 2 days to solidify. The failure of strongly deformed vesicles to become spherical in as long as 2 days suggests that relaxation of deformed vesicles was effectively opposed by yield strength.

Origin of background vesicles

Thin (<0.5 m) flow units tend to be homogeneous, and they and the top crust of all units have a uniform content (25%) of vesicles having a narrow size range (median diameter 2 mm). From these facts it is inferred that lava arriving at the Pedregal was homogeneous and had a uniform population of bubbles inherited at the vent. This population was only a small remnant of the original bubble content: the major part escaped at the vent and gave rise to the explosive activity that constructed the cinder cone and ash blanket there. Any large bubbles still remaining escaped from the lava while flowing through lava tubes toward the Pedregal, and some coalescence also occurred.

During slow extrusion of lava from tubes in the Pedregal a foliation and lineation were imposed on the lava, and vesicle coalescence caused bubbles to grow sufficiently that they were able to overcome the yield strength and ascend.

The vesicle distribution is nearly uniform through the thinnest flow-units (Fig.2). As flow-unit thicknesses increase so the distribution becomes increasingly heterogenous. The content of background vesicles in the lower flow interior declines to under 1%, and megavesicles of various kinds come to comprise an increasing proportion of the total vesicle population. These variations are taken to mean that megavesicles formed at the expense of background vesicles.

It is considered that the yield strength of the lava was such as to prevent ascent of background bubbles, and that the heterogeneity was caused by the widespread scavenging of these bubbles by the diapiric rise of pipe bubbles that were large enough to overcome the yield strength. The small and scarce background vesicles in the lower and middle flow interior are interpreted to be remnants that escaped being scavenged.

Origin of side-wedge vesicles

Side-wedge vesicles have a distinctive shape which shows that they pushed aside their floor and roof, and extended laterally by wedging apart the lava.

A few at the top of the zone have a height/width ratio of more than 0.3 and grew predominantly by localized roof uplift. It is clear that some deformed background vesicles coalesced in situ with wedge vesicles, and are partly responsible for the highly irregular shape of the latter.

In normal Hawaiian pahoehoe, megavesicles are rare and the largest vesicle-related voids that rival in size the side-wedge vesicles of Xitle are gas blisters. Gas blisters however have a different origin. They typically occur in a foamy zone in which vesicles are highly concentrated, and the vesicle content and size as well as the extent to which vesicles have coalesced by disruption of vesicle walls increase toward the blister. The blister formed where the foam tore and produced the distinctive bubble-wall structure along roof and floor of each blister. Blisters resulted from the in situ coalescence of background vesicles.

The side-wedge vesicles in Xitle lava are different because they do not occur in foamy zones, and the vesicle size and amount do not increase toward them. This, combined with their discordance to and disturbance of the foliation, indicates that they resulted from the arrival of large bubbles that ascended from lower in the flow. The bubbles expanded mainly by extending laterally in the steep viscosity/rheology gradient just beneath the surface crust.

The side-wedge vesicle zone records the arrival of large bubbles over a long

time interval. From the known time to form a crust 0.2 to 2 m thick, the first side-wedge vesicles would have arrived in position under the 0.2 m crust about 8 hours after a flow-unit was emplaced and the last under a crust 2 m thick after about 1 month (based on measurements of crustal growth compiled by Wilmoth and Walker, 1993).

Origin of belljar vesicles

The typical absence of a foliation over their top and the fact that they abruptly truncate any pervasive foliation that may exist (Fig. 5a) demonstrate that belljar vesicles did not rise by updoming and pushing the lava aside.

It is postulated instead that bulk subsidence occurred, below a belljar fracture, into an underlying ^{cylindrical} or globular vesicle. The gas in the cylinder or globule ascended into the belljar vesicle as collapse occurred (Fig. 6c). It is envisaged that the lava would have been in the physical condition of a jelly at that time. Segregation material which occurs in a circumferential crack would have been the final fluid fraction to rise.

Positive evidence for collapse is exhibited by belljar vesicles which are exposed in vertical cross-section: a zone of strongly deformed and inwardly inclined background vesicles and microrifts occurs extending below the rim of the belljar (Fig. 6b), and their orientation is consistent with collapse. The concentration of background vesicles below belljar vesicles appears to be generally lower than in the surrounding lava suggesting that some were scavenged during the subsidence event.

Belljar vesicles seem to be somewhat more abundant in tumuli than elsewhere in the lava; possibly the existence of mildly extensional stress conditions favored their formation.

Belljar vesicles constitute a well defined type in the Xitle lava. They are closely similar to "dome vesicles" photographed by McMillan et al (1987) from the Cohassett flow of the Columbia River Plateau. He and his co-workers did not propose a specific mechanism for their formation; exposures of the Cohassett flow seen by the writer are more weathered and much less favorable for study than the Xitle flow.

Now, two types of vesicles having a dome-like aspect are recognized in the Xitle lava that differ fundamentally in their relationship to the foliation and are inferred to have ascended by different mechanisms. Two names, namely belljar and globular vesicles, are hence proposed. Belljar vesicles are broadly similar in form and inferred origin (by subsidence of material below an upwardly-convex fracture accompanied by entry of fluid into the resulting void), but are 3 to 4 orders of magnitude smaller than belljar intrusions (Du Toit, 1920; Ellis, 1945) and underground cauldron subsidences (e.g. ^{as} postulated for the Mourne Mountains

Origin of pipe and cylindrical vesicles

Pipe vesicles in Xitle lava are broadly similar to those in Hawaiian lava. They are interpreted to have a similar origin, by the rise of large bubbles and the failure of lava (because of its yield strength) to close behind the ascending bubble (Walker, 1987). Assuming that the bubbles had a diameter of 100 to 150 mm, (several times greater than the 20 to 30 mm of preserved pipe vesicles) and the density contrast between lava and gas was 2400 kg m^{-3} , the yield strength would have been about 300 to 500 Pa (Sparks et al., 1977). Growth of pipe bubbles to a sufficient size to initiate pipe vesicles was attributed to an inward-forcing mechanism by Wilmoth and Walker (1993).

The Xitle pipe vesicles are much wider (20–30 mm) than pipes in typical Hawaiian pahoehoe (5–20 mm), and have a wider spacing ($>0.1 \text{ m}$ instead of 0.05 m). These differences are regarded as consequences of the higher viscosity and yield strength of the Xitle lava. Few pipe vesicles extend higher than 0.5 m in a flow unit, but cylindrical vesicles occur higher and are interpreted to be the upward extension of late-formed pipe vesicles. Preservation of a cylindrical vesicle and its failure to reach the side-wedge vesicle zone must imply that it was too small to overcome a considerable yield strength (estimated to have been 1000 Pa or more) at that time.

The upflow plunge of pipe vesicles is about 10° steeper than the upflow dip of the foliation. The plunge angle of the pipes is regarded as the resultant of the lateral lava-flow velocity and the ascent velocity of the pipe-forming bubbles. It is evidence that the pipe-forming bubbles were large enough to overcome the yield strength and ascend, while background vesicles were too small to ascend and were passively deformed by flowage.

Origin of inverted-cone vesicles.

The fact that inverted-cone vesicles underlie diapiric cylindrical vesicles implies a closely related origin. From their position and shape, the inverted-cone vesicles are interpreted to be portions of tail that became detached from and were left behind in the wake of cylindrical vesicles.

Origin of globular vesicles

Globular vesicles occur in the middle part of thicker flow units and tend to a spherical shape. They are too large for this shape to be attributed to surface tension alone and gas pressure must be largely responsible. The fact that they are equant in form implies that they expanded in and rose through a medium that was rheologically isotropic. Background vesicles are deformed and have a local foliation that curves over the top of and is parallel to the surface of globular vesicles. This shows that globular vesicles rose diapirically.

Origin of segregation features

Segregation veins, vesicle cylinders, and the floor of segregation vesicles consist of segregated material that lacks abundant olivine microphenocrysts, and is texturally different from normal Xitle basalt. Vesicles are abundant. The segregation material comprises about 1% of the total lava volume and about 50% of it consists of vesicles. The mixture of liquid lava and gas bubbles would have had a positive buoyancy at all levels in the Xitle lava.

Macroscopic segregation features are not observed in lava flow units thinner than about 2 m. One possible explanation is that a load pressure of at least 4.5 kg/cm², equivalent to a 2-m depth in the lava, was required before extraction of residual fluid by filter-press action became effective. Another possibility is that a minimum time of about 8 days (the time taken for upper and lower crusts in a unit 2 m thick to meet at or near the median) was required to segregate the fluid.

Filter pressing has been widely postulated to be responsible for the segregation of residual melt (see, for example, Puffer and Horter, 1993). Diktitaxitic voids (Dickinson and Vigrass, 1965) are however widespread in the interior of Xitle flow units and are a possible source of segregation melt. The lack of evident deformation of these voids would seem to be inconsistent with a filter-pressing origin.

Segregation features do not occur in all flow units thicker than 2 m, and there seems to be a distinct positive correlation between their occurrence and the abundance of pipe vesicles. Pipe vesicles form in flowing lava, and possibly the segregation process is favored by flowage.

Segregation veins evidently formed late in the history of each lava flow-unit, when the middle of the unit was still hot but consisted of a rigid if weak crystal framework. Segregated fluid rose until it reached a level near the median at which the strength of the framework began to increase rapidly upward. Accumulation of segregated fluid at that level then caused dilational stresses

that were relieved by rifting of the framework along a nearly horizontal plane. Segregation fluid entered and extended the rifts laterally to generate segregation veins. Segregation veins locally cut discordantly across a vesicle-foliation. Some segregation vesicles occur on segregation veins at height culminations (Fig.) and evidently formed where the segregated melt with bubbles rose into and accumulated preferentially in the culminations.

Segregation veins were evidently fed from below, through vesicle cylinders and steeply-inclined fissures. A segregation vein 0.05 m thick having a lateral extent of 20 m by 20 m would have a volume of about 20 m^3 and would need to be derived from a considerable ($\sim 2000 \text{ m}^3$) catchment volume. Examples were seen where the same segregation vein is continuous with several vesicle cylinders (and also in one instance with a near-vertical fissure), indicating that each segregation vein may tap fluid arriving from below through multiple channels.

In the thicker flow-units, several segregation veins occur at different levels: thin veins, about 0.005 m thick, occur above the median, and the main vein, about 0.05 m thick, occurs below the median. Possibly the higher veins are earlier, formed at a time when the supply of segregated fluid was small and the crust was thinner. Examples were however noted where an upper vein was connected with a lower main one.

The ability of the segregation fluid to inject laterally and the perfectly level upper surface of segregation material in vesicles suggests a relatively low viscosity. The segregation fluid was still mobile after the rest of the lava had become static, and evidently had a lower melting temperature consistent with the more evolved compositions of segregations (Kuno, 1965). Many vesicles are however deformed — commonly they are of vermiform shape — and some are pipe vesicles suggesting that this fluid possessed a small finite yield strength.

Deep lava-inflation clefts (Walker, 1991) occur in tumuli and at the edges of lava-rises, and the tip of one such cleft was observed to penetrate a segregation vein at a depth of 3 m in the lava. The segregated material formed an ooze-out 0.02 m wide into the lower part of the cleft (about 0.1 m higher than the segregation vein), having a bulbous and upwardly-convex upper surface and containing deformed vesicles having upwardly-convex roof and floor.

Segregation vesicles were noted at this same locality at 2 to 3 m depth in the flow unit. A crust this thick would have taken 1 to 2 months to form. These particular segregation vesicles have flat floors that are tilted about 10° from horizontal (Fig. 10d). The tilting is localized in a tumulus, and the gashes into which the segregation fluid oozed were still forming when the tilting occurred. This shows that development of tumuli in the Xitle lava by localized injection of lava beneath a surface crust and movement of segregation fluid were still in progress 1 to 2 months after the flow units erupted.

SUMMARY AND CONCLUSIONS

The Xitle lava of the Pedregal de San Angel hosts a spectacular array of (>0.1 m in diameter) megavesicles including types that have not previously been described. Much of the lava possesses a pervasive foliation that is defined by small flattened vesicles. The fact that this foliation is commonly non-parallel with flow-unit margins permits inferences being made of the rheological condition of the lava. The fact that some megavesicles are discordant to, and have not disturbed, the foliation while others have disturbed it and also generated a local foliation, leads to the identification of several contrasting modes of megavesicle ascent and growth and enables evolution of the vesicle pattern to be inferred.

This paper proposes a model, the essence of which is that a uniform population of small vesicles comprising 20 to 25% of the lava volume and inherited at the vent was initially present in the lava when it reached the Pedregal. In the thinnest flow-units this population survived almost unchanged apart from inward vesicle growth by coalescence. In the thicker flow units only remnants of this population (grown by coalescence) survive as "background vesicles", and most were scavenged by large ascending bubbles and incorporated into megavesicles.

A variety of megavesicle types developed, and show a zonal distribution. "side-wedge" vesicles accumulated in the upper flow interior and widened by wedge action, and their distinctive form was determined by their growth below a surface crust in a steep rheology gradient. Each "belljar" vesicle rose to occupy a space resulting while mass-subsidence of a lava-volume into a large bubble occurred. In contrast "globular" vesicles (which are similar in size) rose diapirically through the lava. Belljar and globular vesicles occur in the flow-interior and have forms that indicate their formation in rheologically-isotropic lava there.

The final dynamic event was the rise of small amounts of segregated melt, in vesicle cylinders and steep fissures, to generate segregation vesicles and veins. These features are found only in the thicker flow units perhaps because a small but finite pressure must be exceeded before filter-press action becomes effective, or because more than a certain minimum time is required for their segregation.

This paper is a contribution to the theme that certain features of the lava structure and vesicle distribution depend on the possession by the lava of an initial small but finite yield strength. When vesicles were deformed, those within a certain size range remained deformed because surface-tension and gas-pressure forces were not sufficiently strong to overcome the yield strength. Megavesicles formed because only bubbles large enough to overcome the yield strength could ascend, and these bubbles grew rapidly by scavenging smaller bubbles. The generation and preservation of megavesicles in the Xitle lava is attributed to the yield strength.