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Tubular Voids within Labradorite Phenocrysts from Sonora, Mexico

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Abstract

Basaltic rocks in the Pinacate volcanic field of northwestern Sonora, Mexico, contain small-to-remarkably-large phenocrysts of labradorite. Best displayed within the more transparent of these phenocrysts are subspherical to tubular voids that are believed to represent fluid inclusions of primary origin. The voids range in diameter from less than 100 microns to as much as 2 mm, and some of the tubular ones are 1 cm or more in length. The tubes typically occur in families of a few to several tens of mutually parallel individuals within a single phenocryst. In most instances they are aligned parallel to some specific growth direction within the host crystal, and commonly they are oriented perpendicular or nearly so to a crystal face. They pinch and swell along their lengths, and either are entirely sealed within the host or open upon the margin of the crystal.

It is here suggested that fluid bubbles, nucleating on the surfaces of growing crystals, may have poisoned the crystal-liquid interface and thus may have become partly included in the phenocrysts. If the fluid were exsolving from the magma as a crystal grew, each included bubble would also tend to grow. Crystal and bubble thus might grow outward together, and primary tubular fluid inclusions would result. Variations in growth rate of a crystal *vis a vis* that of its included bubbles could account for pinching and swelling of tubes and other textural features.

Introduction

Basaltic rocks exposed in the Pinacate volcanic field of northwestern Sonora, Mexico, are alkali basalts and hawaiites of late Pleistocene age. Pyroclastic activity must have been notably abundant here, for the field is densely populated with hundreds of cinder cones. Lavas of the Pinacate are typified petrographically by their porphyritic character; most units contain scattered to very numerous phenocrysts of labradorite, olivine (near Fo_{80}), augite, and magnetite. These crystals attain remarkably large size in many volcanic units. Crystals of labradorite range smoothly upward in size from groundmass grains to individual tablets at least ten cm long. The other phases attain comparable, although somewhat lesser, dimensions.

Many of the large labradorite crystals are virtually transparent, pale citrine to nearly colorless, and of gem quality. Others are riddled with included blebs and plates of groundmass material and/or glass. In thin section, the phenocrysts of all types and sizes exhibit an array of shapes and textures, many of which resemble the skeletal forms typically developed among crystals that grew rapidly in response to conditions of supersaturation. Comparable textures in crystals of olivine have been described by Drever and Johnston (1957). Similar textures appear in crystals of feldspar produced experimentally at high growth rates by W. C. Luth and Phillip M. Fenn (Luth, personal communication, 1973). Skeletal textures in Pinacate phenocrysts were described briefly by Gutmann (1972a) and will be more fully illustrated in a forthcoming contribution.

The phenocrysts of all types and sizes contain voids. In most instances these voids merely reflect vesiculation, upon eruption, within included basalt melt. In many other instances, the voids must represent large, tubular, fluid inclusions that now are essentially empty. To the writer's knowledge, such textural features have not hitherto been reported; the purpose of this paper is to describe these curious tubular voids and offer suggestions as to their significance.

The remarkable transparency of the labradorite phenocrysts affords an unusually good opportunity to observe their internal textural features in three dimensions. This is especially true of the large, gem-quality crystals occurring as individual megacrysts in loose pyroclastic accumulations. The material described and illustrated in this paper was collected from cinder cones located at or near Crater Elegante, in the eastern part of the volcanic field.

The Pinacate volcanic field has been mapped by Michael F. Donnelly (report in preparation); a report on the collapse depressions in the field was presented by Jahns (1959); and the rocks in and around Crater Elegante were described by Gutmann (1972b).

Textural Description

Tubular Voids

Voids of various shapes have been observed in phenocrysts of all four of the principal phases, but the tubular voids are best displayed and evidently occur most abundantly in plagioclase. The tubes are circular in cross section (Fig. 1) and range in diameter from a few tens of μm to as much as 2 mm. Most of them are straight and markedly elongate, with some observed lengths in excess of 1 cm. They extend from deep within a crystal outward toward or to its surface. Where that surface is planar or nearly so, the tubes commonly are oriented perpendicular to it (Fig. 2).

Length-to-width ratios of the tubes vary considerably, and one can trace all gradations from tiny, spherical bubbles a few tens of μm in diameter through ovoid bubbles to stubby tubes and finally to markedly elongate tubes with length-to-width ratios as great as 100:1. The tubes pinch and swell along their length in many crystals (Fig. 2), and numerous tubes are entirely sealed within the host crystals (Fig. 3).

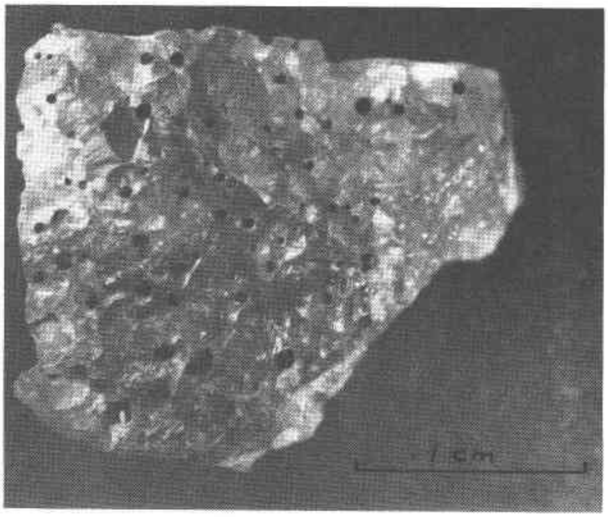

FIG. 1. Fragment of labradorite phenocryst containing numerous parallel tubes, here viewed end-on.

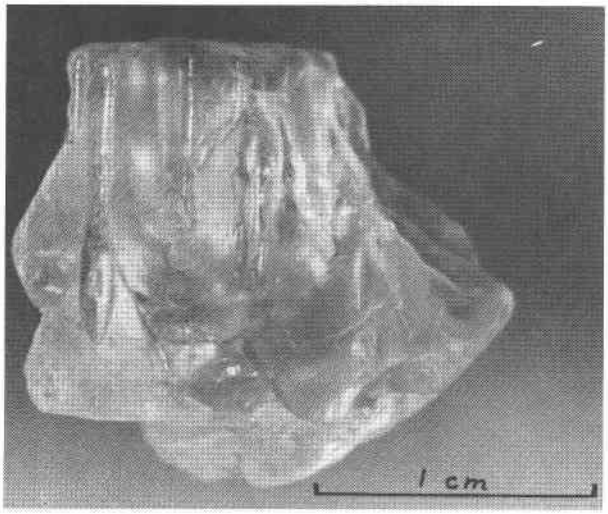

FIG. 2. Parallel tubular voids in broken labradorite phenocryst. Tubes pinch and swell along their length and are oriented perpendicular to a (010) crystal face (top of view).

Some tubes that open upon the phenocryst margins contain films of basaltic glass near their mouths, whereas others are devoid of glass. However glass is completely absent from most tubes or bubbles that are entirely sealed within their crystal hosts. A few of the large sealed tubes contain barely visible traces of a reddish brown, dust-like material, the

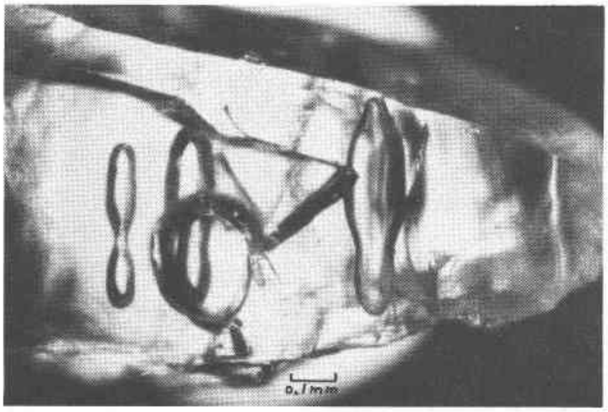

FIG. 3. Fragment of labradorite completely enclosing three parallel tubular voids.

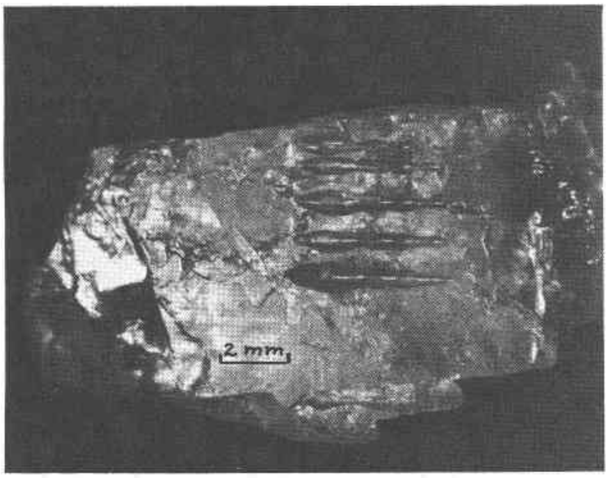

FIG. 4. Labradorite phenocryst containing five tubular voids that pinch and swell in the same places along their parallel axes. All five tubes are coterminal on each end, although the lighting obscures the outer termination of one tube.

composition of which has not been determined. The absence of glass from the sealed tubes strongly suggests that the tubular forms do not represent voids produced during vesiculation of included (or partially included) basaltic melt.

The tubular voids typically occur in groups of several to as many as 50 mutually parallel individuals per phenocryst (Figs. 1, 2). All of the tubes in a given crystal are parallel not only to one another but also to some specific crystallographic direction. Where the tubes open upon or are located near a crystal face, they are oriented perpendicular to that face. Many of the specimens collected from pyroclastic units represent crystal fragments bounded chiefly by cleavage surfaces; tubes in these samples typically are perpendicular to the (010) or (001) cleavage. The crystals themselves commonly are grossly euhedral and vary in habit from tabular parallel to (010) through blocky to elongate parallel to *a*. Their forms can be either simple or notably complex and modified by several minor pinacoids. The tubes most commonly are oriented perpendicular to a (010) face, although orientations perpendicular to (001) also are common, and several other orientations occur.

Only four among many hundreds of phenocrysts examined by the writer were found to contain two sets of tubes. The two sets differ from one another in crystallographic orientation and are *located in different parts of the host crystal*. None of the phenocrysts examined thus far contain more than two sets.

The frequency of occurrence of tubes in large plagioclase crystals is such that 12 among 107 phenocrysts collected from one cinder cone contain multiple tubular voids. Tubes evidently are rather less common in labradorite crystals from most of the other Pinacate cinder cones and seem rare and poorly developed among phenocrysts of olivine, augite, and magnetite. Tubular voids seem much more common among plagioclase phenocrysts from pyroclastic units than among those from lava flows; however, this disparity might reflect the relative inaccessibility of the latter to detailed examination.

All tubes in a single crystal tend to be about the same length and width, although each tube can vary in width along its length. In numerous instances, where one tube in a family pinches and swells, most or all other tubes in that group pinch and swell by comparable amounts and in the same places along the tube axis. One or both ends of all tubes in a family thus tend to appear or pinch out together (Fig. 4). In several transparent crystals, groups of bubbles or the inner terminations of tubular voids define a plane within the crystal parallel to a nearby crystal face (Fig. 5). The tubes extend out toward this face and are perpendicular to it.

Associated Textures: Small Fluid Inclusions

Except for secondary fluid inclusions arranged in curving sheets, fluid inclusions less than about 10 μm across seem to be rare. A few tiny, isolated, roughly spherical inclusions, with refractive indices

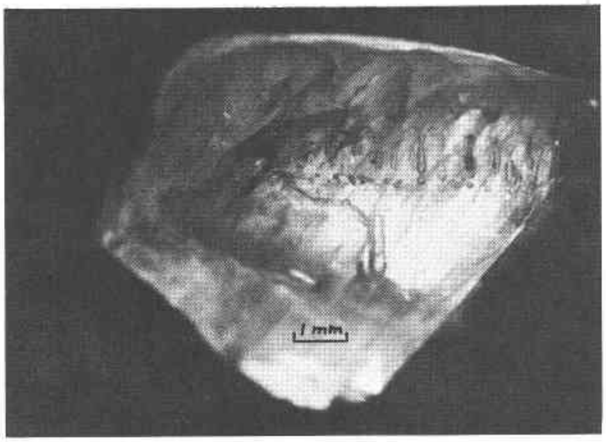

FIG. 5. Fragment of labradorite phenocryst containing numerous bubbles arranged in a zone parallel to a nearby crystal face (top of view). Note tubular voids extending toward and oriented perpendicular to the crystal face.

much less than that of the enclosing labradorite, have been observed. In two cases, such an inclusion contained a minute bubble that occasionally was in Brownian motion. Some of the feldspar phenocrysts contain numerous inclusions of basalt glass; the glass blebs include tiny fluid bubbles. Although the ratio of glass to associated gas appears to be constant in many instances, some crystals or domains within crystals clearly contain inclusions in which the amount of fluid is greatly in excess of that of any associated glass (Fig. 6). Such fluid inclusions are invariably associated with a train of much smaller, secondary inclusions emanating from the larger bubble and perhaps indicating leakage from it. Similar trains of secondary inclusions emanate along conchoidal fractures from sealed tubular voids, suggesting loss of fluid from these much larger inclusions as well. Fluid loss from both small and especially from large inclusions in feldspar might be reasonably expected to attend sudden relief of confining pressure during pyroclastic eruption.

Relationship between Tubular Voids and Zoning of Phenocrysts

Tubular voids have not been identified with certainty in the small phenocrysts normally encountered in rock thin sections. In view of the large number of phenocrysts examined, their apparent absence cannot be wholly ascribed to the fortuitous orientation required, wherein the axis of a tube must lie in the plane of the section. Essential absence of the third dimension leaves doubt as to whether an elongate re-entrant in the margin of a phenocryst truly represents a tube in longitudinal section or merely the outline of a platy re-entrant of vesicular groundmass material that was cut by the section. Numerous such re-entrants were observed, and oscillatory zoning, where present, wraps around into the mouth of each re-entrant and trends parallel to its walls, rather than being transected by them. However, almost all such re-entrants thus far encountered in thin sections of labradorite crystals less than 1 cm across contain at least a trace of groundmass material and may well represent inclusions of highly vesicular basalt rather than tubular voids. Tubular voids have not been observed with a hand lens in labradorite crystals less than 0.8 cm long.

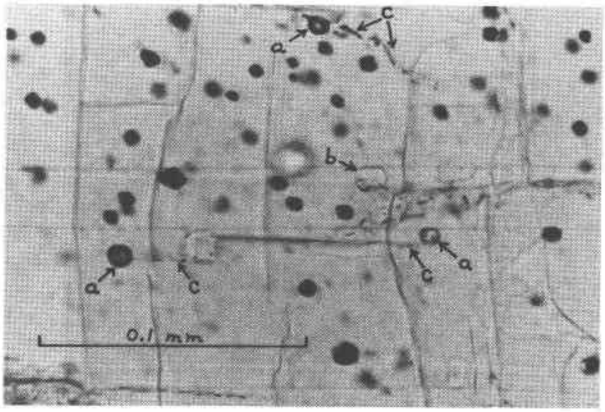

FIG. 6. Detail of labradorite phenocryst in thin section. Note primary inclusions of glass and of fluid (see arrows **a**). Certain of the fluid inclusions are transected by the upper surface of the section, are filled with balsam, and reveal negative crystal form (see arrow **b**). Also note trains of secondary fluid inclusions emanating from the larger bubbles (see arrows **c**).

Several precisely oriented thin sections were prepared from individual labradorite megacrysts containing mesoscopically visible tubular voids. The large feldspar crystals are remarkably homogeneous in composition but typically exhibit fine-scale oscillatory zoning through a very narrow (<1 percent An) compositional range. Where the mouths of open tubes are lined with glass, oscillatory zones paralleling the margins of the crystal wrap down into and trend parallel to the walls of the tubes. Where tubes are devoid of glass, barely discernible fine-scale oscillatory zonation, defining planar growth surfaces to which the tubes are perpendicular, apparently is truncated or barely deflected inward upon encountering the tube. These textural relationships resemble in many respects those described by Blackerby (1968) from plagioclase phenocrysts in andesitic basalts. The re-entrants described in thin section by Blackerby are filled with glass and are characterized by the development of oscillatory zonation trending parallel to their walls (convolute zoning) rather than by apparent truncation of zones, although some truncation was observed (Blackerby, 1968, p. 957, 959, Fig. 4a).

Circular to oval holes, with or without associated groundmass material, appear in thin sections of small plagioclase phenocrysts. Absence of the third dimension obviously precludes identification of these holes as tubular voids cut by the section, although many may represent just that. Compositional zonation, where present adjacent to such voids, commonly is represented by relatively broad zones that are deflected around the margins of the circular holes. In some instances, these zones are identical in composition with zones present at the outer margins of the crystals. This suggests that the circular "holes" are connected to the outside of these crystals in the third dimension.

Discussion

Several textural features of the tubular voids indicate that these must represent pipe-like fluid inclusions of primary origin. The common occurrence of tubes entirely sealed within their host crystal and devoid of any trace of associated glass or groundmass material implies that the tubular voids were filled solely with fluid while the phenocryst was still growing in basaltic magma. The spectrum from spherical and ellipsoidal bubbles to markedly elongate tubular voids suggests that all these units are textural manifestations of the same phenomenon; the fact that groups of bubbles and/or the ends of tubes within a given transparent crystal commonly define a plane or zone parallel to a nearby growth face strongly suggests that the bubbles and tubes represent fluid included while the crystal grew. The large size, straight tubular form, and orientation perpendicular to a growth face are likewise compatible with a primary origin.

It is here suggested that fluid bubbles nucleating on the surfaces of growing crystals may have poisoned the crystal-liquid interface and thus may have become partly included in the phenocryst. One might expect that fluid bubbles would tend to rise in basalt liquids. In many instances, then, bubbles might "pop off" the crystal surfaces when they attained sufficient size. If the rate of forward propagation of a given crystal face were sufficiently rapid relative to the rate of growth of a bubble, however, that bubble might become largely incorporated in the crystal.

If fluid were exsolving from the magma at the same time, the bubble itself would tend to grow. Crystal and bubble thus might grow outward together, and primary tubular fluid inclusions would result if the growth rate of a crystal face were nearly the same as the growth rate of bubbles associated with that face. Slight variations in growth rates might result in pinching or swelling of tubes, as might slight fluctuations in pressure within the magmatic system. Presumably, only one pinacoid of any given labradorite crystal would have a rate of outward propagation appropriate for the development of tubes; thus, all tubular voids in that phenocryst should, in general, be mutually parallel.

If the growth rate of a crystal decreased relative to that of the fluid phase, the bubble would eventually break free and rise, perhaps taking with it fluid within some or all of the tube. The tube would then become partly or wholly filled with melt. Alternatively, a relative increase in the rate of crystal growth might result in complete inclusion of the tube.

In many instances, tube growth must have persisted so that the tubular voids now open upon the margins of such crystals. The presence of glass lining the mouths of many open tubes may well reflect substantial fluctuations in pressure within the basaltic magma shortly before pyroclastic eruption.

Implicit in the above discussion is that significant volumes of fluid were exsolving from the basaltic magmas while the labradorite phenocrysts grew. CO_2 is nearly insoluble in basaltic liquids at pressures less than about 10 kbar (Hill and Boettcher, 1970; Holloway and Burnham, 1972). Phenocryst-groundmass compositional relationships, the essential absence from Pinacate basalts of high-pressure megacrystic phases (*e.g.*, spinel, sodic plagioclase, anorthoclase), and the appearance of abundant plagioclase near the liquidus during phenocryst growth suggest that the labradorite phenocrysts grew at pressures significantly less than 10 kbar and perhaps much less. Very small quantities of CO_2 probably exsolved from the basaltic liquids during their ascent from the mantle. However, the remarkable compositional homogeneity of many of the large labradorite phenocrysts strongly suggests that they did not grow synchronously with release of large amounts of confining pressure. Phenocrysts containing tubular voids occur in volcanic units consisting of as much as 95 percent glass or groundmass. Therefore exsolution of a fluid phase cannot be ascribed to saturation with water attendant upon crystallization of a great percentage of basaltic magma.

It has been suggested that many Pinacate phenocrysts grew rapidly and at relatively shallow depths (Gutmann, 1972a,b). If the magmas were either saturated or nearly so with respect to an aqueous phase as the crystals grew, the increase in water content of the boundary-layer liquid adjacent to growing, nominally anhydrous phenocrysts would result in exsolution of an aqueous fluid at the crystal margins. Alternatively, if the labradorite phenocrysts were indeed growing at a relatively rapid rate, evolution of aqueous bubbles at the crystal-liquid interface could occur even in magmas undersaturated with an aqueous phase, as demonstrated experimentally by Fenn and Luth (1973). This would reflect a slow rate of diffusion of the water held in the melt relative to the rate of increase of water concentration adjacent to the growing crystals.

Exsolved water molecules might collect to form a thin fluid film on the surfaces of growing crystals, as envisioned by Neumann (1948, p. 82). Aqueous fluid derived from the film and/or from adjacent, water-saturated magma might also collect sufficiently to permit nucleation of bubbles on the surfaces of the crystals, as suggested by Jahns and Burnham (1969, p. 856). If the meniscus of a bubble represented an effective barrier to diffusion of constituents to the growing crystal face, the bubble would poison the growth surface and tubular inclusions could form in the manner described above. The geometry of the situation suggests that successively added layers of feldspar (compositional zones) should, in general, appear truncated by the tube when viewed in a thin section cut parallel to the tube axis.

That the meniscus of a water bubble in a silicate melt represents a high-energy interface and an effective barrier to migration of diffusing constituents is supported by the experimental evidence of Burnham and Jahns (1962). In the process of determining the solubility of water in albite and granitic pegmatite melts, these workers noted that aqueous bubbles tended to remain trapped in the charges even if the melt was undersaturated with water during the run. Comparison of their solubility data with those obtained by Goranson (1931) indicates that aqueous bubbles can persist even at overpressures of the order of 1 kbar (Burnham and Jahns, 1962, p. 729–730, 740, Fig. 8). These observations indicate that diffusion of water is markedly retarded across the boundaries of the bubbles; it does not seem unreasonable to suggest that diffusion of other constituents to a growing crystal would be similarly retarded by the menisci.

Experimental evidence directly supporting the role of the meniscus of an aqueous bubble in a silicate melt is presented by Fenn and Luth (1973). These workers noted that primary fluid inclusions were incorporated in crystals of alkali feldspar grown from melts in the undersaturated region of the system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O. The aqueous inclusions took the form of bubbles and "tubules."

Small tubular voids might be produced in the same fashion by exsolution of CO_2 from the boundary-layer liquid. However, order-of-magnitude calculations suggest that sufficient volumes of CO_2 probably could not be generated in this manner from basaltic liquid except at such low pressures that concomitant evolution of water would be volumetrically as important or more so. Further petrographic and petrologic data concerning Pinacate lavas must await publication in a forthcoming contribution, wherein the arguments concerning depths and rates of phenocryst growth will be examined in detail.

The model proposed above carries important implications regarding the genesis of labradorite phenocrysts from Pinacate magmas. If the phenocrysts did in fact form at pressures significantly less than 10 kbar, one is led toward the somewhat unorthodox proposition that very large phenocrysts can be generated at very shallow depths indeed, since the evolution of appreciable amounts of water from basaltic liquids presumably does not commence until pressures decrease to the order of 1 kbar or less. Alternatively, if the tubes represent inclusions of aqueous fluid derived from melts which, in bulk, were undersaturated with water, then the large host crystals must have grown rapidly relative to the phenocrysts of most volcanic rocks.

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