

SEGREGATION VESICLES IN BASALTIC LAVA

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ABSTRACT. The dark fine-grained igneous material lining vesicles in amygdaloidal basaltic lavas from Walli, New South Wales, Australia, represents solidified residual melt which moved into early-formed vesicles before consolidation of the lava. In this manner *segregation vesicles* were produced, so named because of the genetic similarity with the segregation veins of Kuno and others (1957). The effect probably represents an increase in the confining pressure applied to the fluid within the vesicles. Partial crystallization of a vesicular lava followed by completion of crystallization at a higher confining pressure (for example, at a deeper marine environment) could produce the observed features. The pervasive low-grade regional metamorphism was in no way involved in the production of the segregation vesicles.

INTRODUCTION

A common feature of amygdules in certain Ordovician basaltic lavas at Cliefden, 35 miles (55 km) south of the city of Orange in the central west of New South Wales, Australia, is a dark, fine-grained lining containing tiny skeletal feldspar crystals. This lining is always much finer-grained than the surrounding host rock-material. Examples are mostly found in fine-grained basalts, many of which have pillow structures.

Labile sedimentary and pyroclastic rocks are closely associated with the basic lavas, and all show extensive mineral alteration on a regional scale. Authigenic albite, chlorite, epidote, prehnite, pumpellyite, sphene, and calcite all appear in both the volcanic and sedimentary rocks. From such evidence it is concluded that the secondary minerals, including albite, formed as a result of low-grade regional metamorphism of the prehnite-pumpellyite metagraywacke facies. Albite, which characteristically forms phenocrysts and microlites in the lavas, apparently is pseudomorphic after original calcic plagioclase.

While only limited deductions about the original mineralogy and chemical composition can be made from the study of the present state of the rocks because of the alteration, the relict primary textures are well preserved. Textural relationships form the basis of this study.

The basic lavas and the corresponding pyroclastic rocks are grouped stratigraphically as the Walli Andesite, with a probable thickness in excess of 4000 feet (1100 m). This formation is overlain by the Ordovician Cliefden Caves Limestone (Stevens, 1952; Smith, 1966), but its specific age is unknown.

PETROGRAPHY

The basaltic lavas of the Walli Andesite generally have pillow structures associated with minor amounts of brecciated volcanic material. The pillows are typically 1 or 2 meters in diameter and are separated by a thin zone, 1 to 2 millimeters across, of interpillow material. The amygdules with linings occur in pillow cores but also occur in lavas that do not have pillow structures.

The rocks are sparsely porphyritic having rare glomeroporphyritic clusters of plagioclase and clinopyroxene phenocrysts scattered throughout an intersertal groundmass of plagioclase microlites, intergranular clinopyroxene and magnetite, and interstitial chlorite. In the groundmass microlites of plagioclase reach 0.25 to 0.30 millimeter in length, while clinopyroxene and magnetite reach 0.1 millimeter in diameter. The interstitial chlorite is generally free from dusty inclusions where the groundmass is relatively coarse, and large magnetite euhedra (up to 0.1 mm diam.) and sphene granules are common. Where the groundmass is finer-grained the magnetite euhedra are smaller, and, in addition, tiny dusty opaque specks are abundant throughout the chlorite. Epidote, prehnite, and pumpellyite commonly occur in a patchy manner throughout the groundmass and in some cases partly or completely replace microlites. Amygdules, ranging in size from subspherical ones 1 millimeter in diameter to others markedly ellipsoidal 10 millimeters in length and about 1 millimeter in smallest diameter, occur within this groundmass.

The amygdule lining and its associated features can be described under the following headings, with reference to figure 1: the *principal surface* which outlines the amygdule, the *lining*, the *subsidiary surface* marking the inside of the lining, and the enclosed *central zone*.

Principal surface.—The principal surface marks the discontinuity in texture existing between the surrounding groundmass and the lining. It is typically subspherical or subellipsoidal in shape (fig. 1A, pls. 1, 2).

Lining.—The material forming the zone adjacent to the surrounding groundmass is called the lining. It consists dominantly of dark dusty material containing, in random distribution, a subordinate amount of thin, skeletal microlites of plagioclase which rarely reach a length greater than 0.10 millimeter (pls. 3, 5). In some specimens delicate brush-like patterns, reminiscent of a variolitic texture, are visible in the lining. The present characters of the lining suggest the former abundant occurrence of glass, now devitrified. The place of glass is taken by the secondary minerals. Microlites are smaller and less abundant in the lining than in the surrounding groundmass. The dusty material consists of abundant opaque specks scattered throughout a base of chlorite, sphene, epidote, and pumpellyite. The opaque specks occur in skeletal groups, as outlines to an unknown acicular primary phase (now pseudomorphed by an aggregate of sphene and epidote), or randomly distributed throughout the base. Relict pyroxene has not been identified in the lining.

Subsidiary surface.—The subsidiary surface marks the separation between the lining and the central zone. The surface is typically irregular in shape but is generally a combination of curvilinear surfaces (fig. 1B). In less common examples it is subspherical or subellipsoidal in shape resembling the principal surface (fig. 1C).

Central zone.—The central zone, enclosed within the lining, generally contains chlorite and calcite, with lesser amounts of quartz, epidote, prehnite, and pumpellyite. In some specimens, a thin concretionary

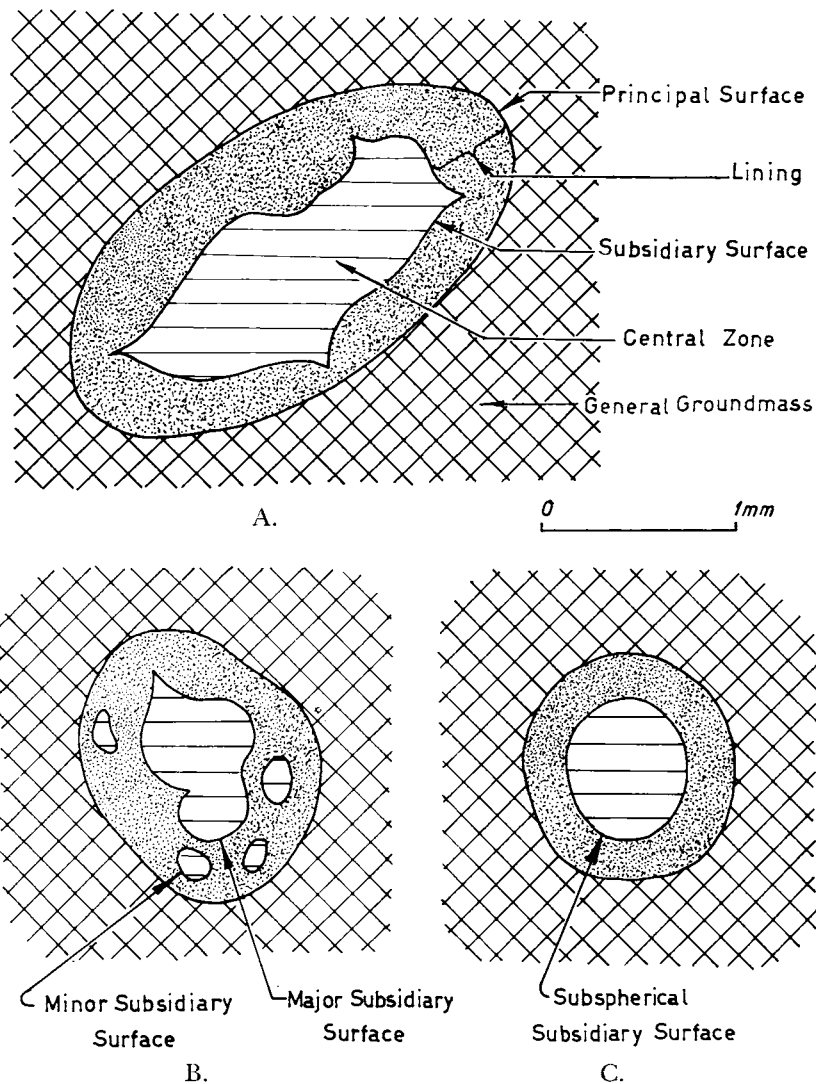


Fig. 1. Generalized diagrams of segregation vesicles, showing terminology used in the description.

banding within the central zone and parallel to the subsidiary surface is still visible despite replacement by these minerals. Relict igneous textures do not exist in the central zone.

Volume measurements

Six specimens from a single flow, each characterized by approximately regular principal and subsidiary surfaces, were selected for quantitative study. The true diameter of the space enclosed by the principal sur-

face varied between 1 and 4 millimeters, while the corresponding true diameter of that of the subsidiary surface varied between 0.5 and 2.5 millimeters. The volume (V_1) contained within each principal surface was calculated and compared with the volume (V_2) contained within each corresponding subsidiary surface. The ratio V_1/V_2 averaged 2.4. The values of this ratio for the six specimens did not differ markedly from the average, table 1.

INTERPRETATION

The principal surface appears to represent the stable interface between a fluid (probably gaseous) and the early melt. Consequently it is interpreted as the *early vesicle outline*. Partial crystallization of the melt at this early stage appears to have established a rigid framework built chiefly of plagioclase laths and stumpy clinopyroxene prisms. This framework preserved the outline of the early vesicles.

From a detailed textural examination of the material (pls. 1-5), it is evident that the dark vesicle linings, with relict igneous characters such as skeletal plagioclase microlites, were initiated during the primary cooling of the lava bodies. The lining has a texture typical of chilled melt that has subsequently devitrified (pls. 3, 5). In addition it appears to be comparable in mineralogy and composition to the interstitial material of the surrounding groundmass. It seems likely, therefore, that the lining represents residual melt that moved into the early-formed vesicles from the surrounding groundmass. In the groundmass precipitating plagioclase molecules were continually added to the plagioclase microlite sites that had nucleated at an early stage. Subsequent nucleations were not common during the cooling. As a result, in the central parts of lavas or pillows where cooling was slow, the majority of plagioclase crystals are relatively large laths, 0.25 to 0.30 millimeter in length, and skeletal plagioclase laths are scarce. This texture contrasts with that of the vesicle

TABLE 1
Volume measurements on segregation vesicles from one lava flow

| Specimen number* | d_1 (mm) | d_2 (mm) | V_1/V_2 |
|------------------|------------|------------|-----------|
| 35016 | 1½ to 2½ | 1 to 2 | 2.46 |
| 35018-1 | 2 to 4 | 1½ to 3 | 2.33 |
| 35018-2 | 1½ to 4 | 1 to 1½ | 2.29 |
| 35018-3 | 1½ to 3 | 1 to 2½ | 2.97 |
| 35093 | 1 to 2 | ½ to 1½ | 2.31 |
| 35099 | 1 to 2 | ½ to 1½ | 1.9 |
| Average value | | | 2.4 |

The specimens were selected from one outcrop of the lava over an area of 5 square meters.

* Numbers of specimens catalogued at the University of Sydney.

d_1 : diameter of the principal surface, in millimeters.

d_2 : diameter of the subsidiary surface, in millimeters.

V_1/V_2 : ratio of the volume contained within the principal surface to that contained within the subsidiary surface.

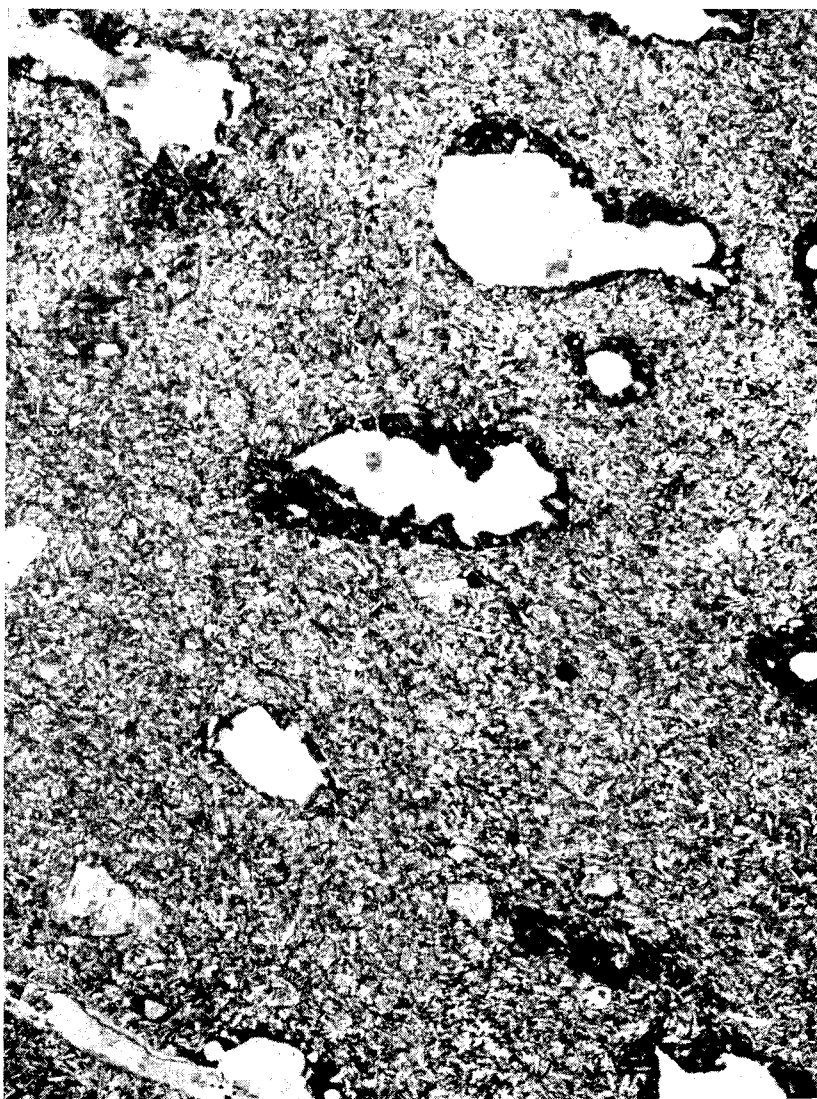
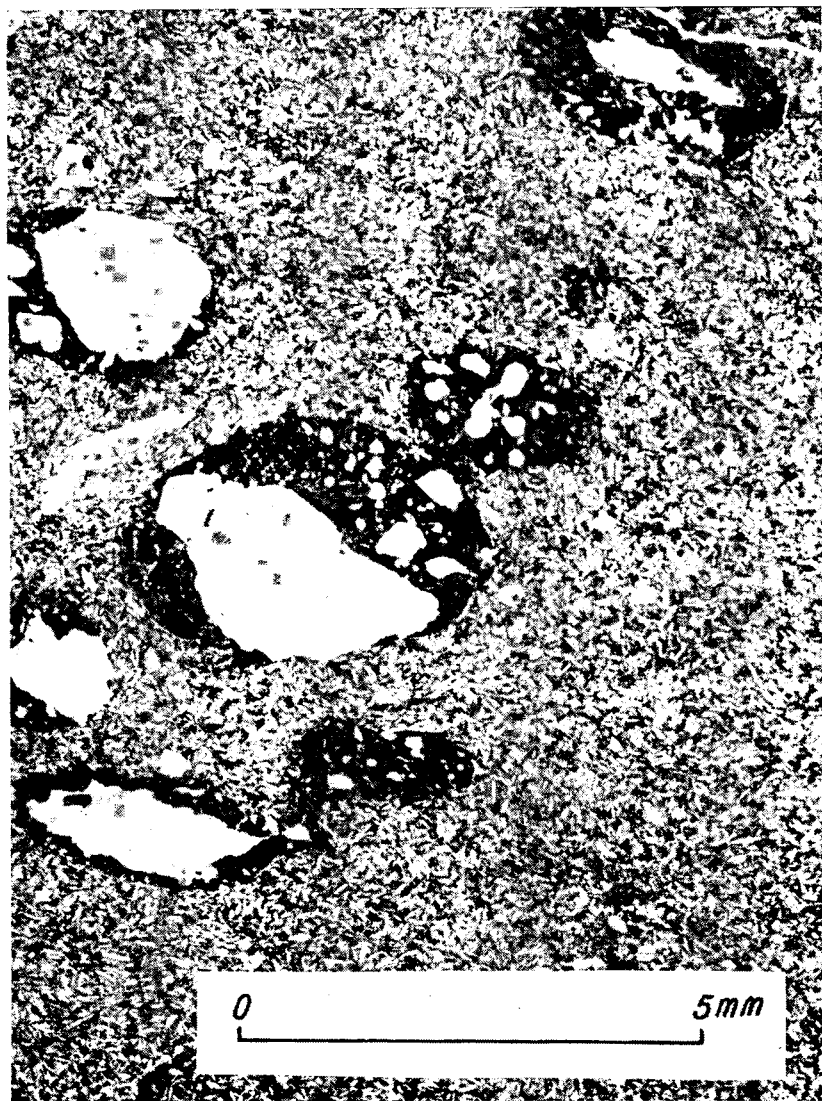


PLATE I



Several segregation vesicles (now amygdules) in a basaltic lava. The light colored central zones contain abundant calcite, with subordinate chlorite, prehnite, pumpellyite, and epidote.



PLATE 2



Enlarged view of segregation vesicle from the same specimen as plate 1, showing the regular subellipsoidal principal surface, irregular major and minor subsidiary surfaces. Calcite and epidote fill the central zone.



PLATE 3



Detail of plate 2 showing the contrast in igneous texture between the general groundmass (left) and the dark lining.

lining where skeletal microlites formed, probably because of the relatively remote position with respect to existing plagioclase sites immediately after segregation and the comparatively short time that remained before crystallization was terminated by cooling.

The subsidiary surface is interpreted as the interface between the segregated melt and the gaseous vesicle fluid. The phases of the central



PLATE 4

Detail of the groundmass of plate 1. Lath-shaped plagioclase microlites (white), granular clinopyroxene (gray with relief), interstitial chlorite (gray) containing abundant magnetite (black) and sphenes.

zone appear to be "normal" amygdule minerals in the accepted sense of Johannsen (1931), that is, post-consolidational vesicle-filling. In the present examples the amygdule minerals probably belong to the metamorphism. Certainly the amygdule mineral assemblages are adjusted to the same metamorphic facies as the secondary minerals in the ground-mass.



PLATE 5

Detail of the lining of the largest segregation vesicle in plate 1. Thin skeletal microlites of plagioclase in a dark base of chlorite, opaque specks, and sphene. White areas represent prehnite and calcite contained within major and minor subsidiary surfaces. Same scale as pl. 4.

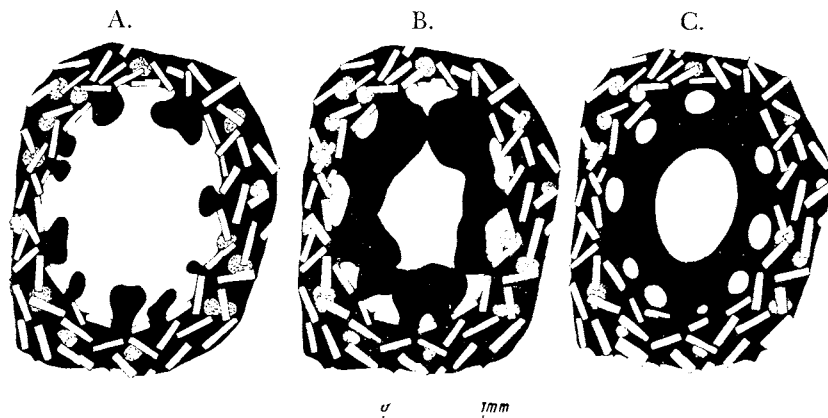


Fig. 2. Successive stages in development of a segregation vesicle. (A) Residual melt flowing into early-formed vesicle. (B) Early vesicle partly filled with residual melt. The shape of both the major and minor subsidiary surfaces is irregular at this stage because the viscosity of the melt is opposing the forces due to surface tension. (C) Stability between the residual melt and the vesicle fluid may finally be reached when surface tension dominates the shape of the subsidiary surface.

The name *segregation vesicle* is proposed for vesicles bearing similar features to those described above because of the genetic similarity with the segregation veins of Kuno and others, (1957) and Kuno, (1965).

Such an origin for certain amygdule materials has been proposed before (Nicholls, 1959), but to the writer's knowledge no observational evidence has been presented in its support.¹ In discussing the significance of the Builth amygdules Nicholls (1959) mentions: "The possibility that gas bubbles formed in the magma at an early stage and later magmatic residual solutions oozed into them should be considered". He then overruled this possibility for the amygdules he was considering since he could find no examples where the amygdule contents matched the composition of late stage solutions. (Nicholls was attempting to explain the chlorite and calcite amygdule fillings). However, in view of the migration of chemical components which are believed to have taken place during alteration (Vallance, 1965), doubt must be cast on the likelihood of finding materials with original magmatic compositions in rocks that have suffered extensive alteration. Probably a more logical reason for dismissing a direct magmatic origin for the Builth amygdules would be the absence of relict igneous textures within the amygdules. The explanation first offered and then rejected by Nicholls, nevertheless, appears to be quite applicable to the dark lining of the amygdules in the rocks of this study. It is clearly *not* relevant to the origin of the amygdule minerals in the central zone (fig. 1).

¹ Since completion of the paper Dr. H. I. Drever (University of St. Andrews, personal communication) directed the author's attention to certain intermediate and basic dike rocks described by Harker (1904, p. 331, 399) where there is unambiguous evidence of infilling of vesicles by residual melt, also in pillow lavas of Bailey and others (1924).

The process proposed by Hopgood (1962) to explain the "dark cloudy rim of varying thickness partly or wholly surrounding amygdules" in a spilitic lava from California cannot account for the Walli Andesite amygdules. Hopgood suggested that crystallites of iron-rich material accumulated against the vesicle margins during expansion of the original vesicle, resulting in a higher concentration of opaques around the vesicle. In such a case it is improbable that the consequent surface marking the limit of the opaque-enriched zone against the general groundmass would frequently be regular (subspherical or subellipsoidal) when the inner vesicle surface is irregular, (fig. 1A, B), as is typical in the Walli Andesite amygdules. In examples such as in figure 1 it is more likely that the regular principal surface is controlled by surface tension and the commonly irregular subsidiary surface is the *accidental surface*, the shape of which is chiefly governed by the rate of viscous flow of the cooling melt.

The evidence may be summarized thus:

1. The regular subspherical or subellipsoidal shape of the principal surface outlines a stable interface between a fluid and the magma early in its cooling history. The fluid was probably of gaseous nature as is common in present day vesicular lavas.
2. The texture of the dark lining has the character of chilled melt.
3. The dark lining resembles interstitial material in the groundmass outside the principal surface. It appears to represent residual melt forced into the early vesicle from the surrounding groundmass.
4. The shape of the subsidiary surface suggests the interface between a viscous liquid and the gaseous vesicle fluid commonly interrupted by cooling before stability could be established, but less commonly in physical equilibrium with the vesicle fluid.
5. The lack of igneous textures in the central zone, together with the concretionary banding in some examples, is strongly suggestive that this zone represents a gas-filled cavity (simply a vesicle) present at the time of final consolidation of the lava. The minerals present in this zone are likely to be normal cavity-filling minerals produced during subsequent regional metamorphism.

Once these points are accepted, a reason for the forcing of residual melt into vesicles (namely, segregation) has to be found.

Theoretical explanation

The following possible explanations for the origin of segregation vesicles seem worthy of consideration:

A. *Shrinkage of gas during cooling, at a constant pressure.*—Consider a basaltic lava where extrusion took place under a specific external pressure, at an initial temperature (T_1), and assuming physical stability between the vesicle fluid and the melt is established, the vesicle fluid pressure would balance the combination of the external pressure, pressure due to depth within the molten lava, and the pressure due to surface tension of the melt. As crystallization proceeds a framework of microlites is gradually formed within the melt and becomes rigid enough

to preserve the shape of early vesicles. During the early stages of cooling while the lava is partly molten, the volume of the vesicle would tend to shrink as a result of the falling temperature, provided the mass of gas in the vesicle remained constant, the extent of shrinkage being governed by the flowage of the melt. If the behavior was that of a perfect gas, the shrinkage due to cooling at a constant external pressure can be calculated from Charles' Law (Schaum, 1946):

that is, if the initial temperature (T_1) was 1150°C or 1423°K,²
 " " final " " (T_2) " 900°C or 1173°K,

$$\frac{V_1}{V_2} = \frac{T_2}{T_1} = 0.83$$

that is, a temperature drop of 250°C from 1150°C would cause the volume of gas to drop by only approximately 17 percent of its original volume³ compared with the measured drop of 58 percent. It seems likely, therefore, that shrinkage due to cooling of the gaseous vesicle fluid while the magma was still partly molten cannot explain the order of magnitude of the observed volume changes.

B. *Escape of gas during cooling.*—If gas had escaped from the vesicle while the magma was partly molten, a reduction in vesicle volume could occur at a constant external pressure. Escape of the gaseous vesicle fluid from the vesicle sites through the melt seems improbable except by rupture of the vesicles at the immediate surface of the flow.

C. *Solubility of vesicle gas in melt increasing with cooling.*—The solubility of the gaseous vesicle fluid in the melt probably would have increased with the decreasing temperature under a constant pressure (Hamilton, Burnham, and Osborn, 1964; Moore, 1965⁴). However, as crystallization progressed, despite an expected increase in the solubility of the gas in the melt, the amount of melt would decrease as the crystal content increased, and so the extent of re-solution and hence the volume change at a constant external pressure of the fluid due to this cause would be limited.

² The order of magnitude of temperatures being based on data from Peck, Moore, Kojima, 1965:

Maximum temperature of magma in Alae Lava Lake 1140°C.

Solidus temperature in Alae Lava Lake below crust of lake 980°C.

The behavior of the gaseous vesicle fluid would probably have departed from that of a perfect gas, but within the expected range of temperature and pressure, the departure is believed to have been slight. As the composition of the vesicle fluid is not known, a more exact treatment is not practicable.

³ However, the early vesicle outline can only be preserved after the stable framework has been established. The temperature drop between this stage and the final solidification of the melt is therefore likely to be less than that quoted, and the shrinkage due to the drop in temperature less than that calculated.

⁴ Data presented by Moore (1965, fig. 2) shows that for the basalts of the east rift zone of Kilauea vesicles with average diameters half a millimeter or more are unlikely to form at ocean depths greater than 1 to 1½ kilometers. These depths correspond to hydrostatic pressures of about 100 to 150 bars. If such a relationship is applicable to the lavas of the present study, then the early vesicle outlines formed at ocean depths of less than about 500 meters, and the final vesicle outlines (the subsidiary surfaces) at depths of not more than 1000 to 1500 meters.

D. *Change in external pressure during cooling.*—Suppose the partly crystalline vesicular magma of case (A) were removed while still hot to a new environment where the external pressure is greater than initially. For simplicity the case is considered where vesicles remain at the same distance from the surface of the lava flow in the new environment as in the initial environment. The vesicle fluid, subjected by medium of the residual melt to a higher confining pressure, would undergo a reduction in volume by the invasion of the early vesicle by the melt, until either stability of pressures is again established, or flowage is terminated by cooling. Meanwhile the relatively rigid framework of microlites retains the early vesicle outline. If the mass of gas remained constant, if the gaseous fluid behaved as a perfect gas, and if flowage allowed stable conditions to be attained, one can relate the vesicle volume change to the change in vesicle fluid pressure by the General Gas Law, (Schaum, 1946):

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}, \text{ or } \frac{P_2}{P_1} = \frac{V_1}{V_2} \times \frac{T_2}{T_1}$$

The measured average change in volume in the examples studied is 2.4. If T_1 was of the order of 1150°C as before and if T_2 was 900°C, then

$$\frac{P_2}{P_1} = 2.0$$

Therefore, if the above hypothesis is correct, and if the temperatures are of the right order of magnitude, V_2 may represent the volume of a gas at a pressure approximately double that existing when the volume was V_1 .

(Surface tension between the melt and the vesicle fluid and the pressure due to it would probably vary with temperature changes, but this factor is unknown.)

Probably the dominant influence on the vesicle volume is the external pressure (Moore, 1965). An increase in external pressure can easily be obtained by submergence in a marine environment. For example, if the initial pressure exerted on a molten lava was one atm (that is, extrusion was at sealevel), then a pressure of two atm can be obtained at a depth of 10 meters in the ocean.

Environment of extrusion

The pillow lavas of the Walli Andesite underlie a thick, widespread sequence of marine sedimentary rocks (Stevens, 1952; Smith, 1966). The immediately overlying formation, the Cliefden Caves Limestone, marks the position of the Molong Geanticline (Packham, ms), which in places shows signs of emergence with an ancient shoreline. If the environment of deposition of the Cliefden Caves Limestone and other marine formations reflects the environment of extrusion of the underlying lavas a sloping marine environment is likely.

CONCLUSIONS

The process of the formation of segregation vesicles is interpreted as being essentially the reverse of that of expansion of vesicles in a magma

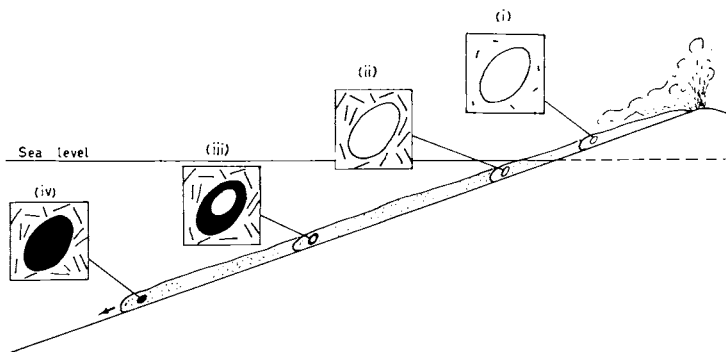


Fig. 3. Possible origin of segregation vesicles during extrusion of a lava flow. The lava at (i) consists of melt, vesicle fluid, plus or minus suspended crystals. At (ii) a relatively rigid framework of crystals is established thereby preserving the shape of vesicles. As slowage continues, the increase in pressure due to submergence forces residual melt into the early vesicles (iii). If flowage continues to sufficient depth, residual melt may be forced to fill the former vesicles (iv) completely. Cooling may interrupt flowage at any stage.

undergoing a drop in confining pressure. The process envisaged simply represents a special case where the process of crystallization appears to have allowed preservation of the early vesicle outlines thereby recording the change in pressure conditions. In the special case where the subsidiary surface represents a stable interface between the vesicle fluid and the segregated melt, it may be possible to calculate semiquantitatively the ratio of pressure change between the early and late environments. However, such a stable relationship relatively late in the cooling history is less likely than earlier, due to the increase in viscosity of melts with cooling.

It seems improbable that the observed volume changes of the vesicles were solely a result of shrinkage of the gaseous vesicle fluid during cooling at a constant confining pressure. Changes in atmospheric pressure (for example, the difference between that present at the summit of a volcano and that at the foot) exerted on a lava flow after its extrusion are also probably insufficient to explain the observed volume changes. However, pressure changes due to the depth of even moderate submergence in water are of the required order of magnitude. If this theory of origin proves to be applicable, then the presence of segregation vesicles may form a useful criterion in the determination of the environment of extrusion of lavas.

The interpretation of volume measurements of segregation vesicles will be further complicated because the environments through which lavas flow often change continuously rather than by discrete steps. If the pressure differences were sufficiently great and if other factors were favorable, the segregated melt may be forced to fill the vesicles completely. The result could easily be misinterpreted as globules of *immiscible liquid*.

It is suggested that segregation vesicles represent the coincidence of certain favorable circumstances that are most likely to occur in a sloping aqueous or marine environment.

Relict igneous characters of the linings indicate the vesicles were partly filled with melt before consolidation of the lava bodies. The later pervasive regional metamorphism was in no way involved in the production of segregation vesicles. A search should be made for rocks bearing these segregation features but with unfilled central zones in unmetamorphosed regions, particularly on the present day sea floor adjacent to shore-lines of volcanic regions.

ACKNOWLEDGMENTS

The research for this paper forms part of a larger study of low-grade regional metamorphism in the central west of New South Wales carried out at the University of Sydney under the financial support of a Commonwealth Research Studentship and the supervision of Associate Professor T. G. Vallance who critically proofread the paper. Helpful discussions with Dr. Ron Vernon are also greatly appreciated.

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