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PILLOW LAVAS AS DEPTH INDICATORS

J. G. JONES

Department of Geology, Imperial College, London S.W. 7, England

ABSTRACT. A prevalent variety of pillow lava in Icelandic intraglacial basaltic volcanoes shows systematic vertical variation in vesicularity and vesicle size which can be related to inferred depth of water at the site of emplacement at the time of eruption. A subsidiary variety of pillow lava shows no such variation and is believed to represent lava partially and variably degassed at a subaerial vent prior to pillow formation. Vesicularity and vesicle size of pillow lava in an Ordovician sequence in Wales suggest a progressive shallowing of the depth of emplacement in water of neritic-bathyal depth.

INTRODUCTION

In an important recent paper Moore (1965) has described a suite of dredge samples, fragments of basalt pillow lava, from the submarine part of the east rift zone of Kilauea volcano, Hawaii: "The vesicularity and bulk density of the basalts show a systematic change with depth. Samples collected from progressively deeper water have higher specific gravity and contain fewer and smaller vesicles". These findings give pillow lavas a new significance as environmental indicators and offer the hope that with further data it may prove possible to infer accurately depths of emplacement of lava both in the present oceans and in the stratigraphic column.[1]

Icelandic intraglacial basaltic volcanoes (Jones, 1966; 1968) offer a unique opportunity for the study of the products of basaltic volcanism in a relatively shallow water environment, in particular pillow lava. These volcanoes are especially valuable in that it is frequently possible to determine with reasonable assurance the surface level of the melt-water ponds within which they grew. This paper examines the vesicularity of the pillow lava of two of these volcanoes in relation to inferred depths of emplacement and uses the Icelandic and Hawaiian data to interpret the pattern of vesicularity in a sequence of Ordovician pillow lava in Wales.

Field procedure in the present study entailed sampling and taking photographs of single pillows of comparable size at fairly regular stratigraphic intervals. Care was taken to select pillows exhibiting a natural cross section normal to the plane of flattening of the pillows. Specimens were taken from the top and bottom of such pillow sections incorporating the outer surfaces.

* Present address: School of Earth Sciences, Macquarie University, N.S.W. 2113, Australia

[1] According to Moore (1965), "the relationship to depth of specific gravity, volume percent vesicles, and size of vesicles indicates that these samples do represent many eruptions at various water depths." However pillow lava is sampled at its site of *emplacement* (the point at which the lava ceased to flow) which presumably may or may not be the site of eruption. It is the vesicularity of the pillow at its site of emplacement that can apparently be correlated with depth. Thus vesicle size and abundance may give us a measure of the depth of emplacement but not necessarily of the depth of eruption.

In this paper the terms "vesicle", "vesicularity", and "vesiculation" refer only to gas cavities of roughly equant dimensions and not to so-called "pipe vesicles" and "vesicle cylinders" (see Waters, 1960), herein termed "pipes". The latter, though ubiquitous in the described pillow lavas (see for instance pls 1-C, D, 3-C), are very variably developed even within the pillows of single outcrops and show no discernable stratigraphically-related pattern of variation.

PILLOW LAVAS OF ICELANDIC INTRAGLACIAL VOLCANOES

Setting of the pillow lavas.—Kalfstindar, one of a group of Quaternary intraglacial basaltic volcanoes in southwest Iceland (Jones, 1968), is believed to be the product of a single eruptive phase. It consists essentially of a pillow lava pile more than 5 km long and 300 m high, surmounted by vitric tuff. Where the tuff pile stands highest the summit at least was demonstrably above the surface level of the meltwater pond for it contains a sequence of typical aa lava flows. The lowest of these flows occurs at 715 m above sealevel, while pillow lava outcrops to 585 m and breccia diagnostic of aqueous conditions to 600 m. The water level thus lay between 600 and 715 m and is subsequently assumed to have stood at 700 m. This value could be as much as 100 m too high, but this is thought unlikely. Levels in the Kalfstindar pile are subsequently designated as depths relative to a water level at 700 m above sealevel.

Raudafell-Hognhofdi is one of the same group of volcanoes. It consists basically of a pillow lava pile 9 km long, 3 km wide, and 300 m high, surmounted by two separate piles of tuff, pillow lava, and breccia capped by aa lava flows. These separate piles, which constitute the mountains Raudafell and Hognhofdi, are collectively referred to as the superstructure. The surface level of the meltwater pond within which the volcano grew is recorded in a downward passage from aa lava flows to palagonitized, glassy flow-foot breccia at a level of 800 m above sealevel in the superstructure of the volcano. Levels in the Raudafell-Hognhofdi pile are subsequently designated as depths relative to a water level at 800 m above sealevel.

Two varieties of pillow lava, designated type 1 and type 2, can be recognized. Type 1 pillow lavas are a dull lusterless gray in contrast to the much lighter-appearing type 2. The latter often display plagioclase phenocrysts less than 1 mm in diameter, seen under the microscope to be clots of minute laths. Type 1 forms the basal pillow lava piles of Kalfstindar and Raudafell-Hognhofdi. Type 2 pillow lava, absent from Kalfstindar, occurs as pods and lenses embedded in the tuff and breccia of the Raudafell-Hognhofdi superstructure.

Depth trends in type 1 pillow lava.—Plates 1 and 2 show photos of sections of single pillows taken on approximately linear traverses up the flanks of the pillow lava piles of Kalfstindar and Raudafell-Hognhofdi. The vertical separation between the top and bottom pillow in each traverse is 280 m and 220 m respectively. These photos demonstrate a conspicuous increase in pillow vesicularity with decreasing depth, accompanied by the appearance and progressive intensification of concentric zonation of vesicles in the more vesicular upper halves of the pillows.

The trends shown in plates 1 and 2 are characteristic of pillow lava of the basal piles. In the field it is the absence or presence and intensity of vesicle zonation that is most readily observed. Conspicuously zoned pillows are predominant at depths of less than 350 m and rare below 450 m, and conversely faintly zoned or unzoned pillows are predominant below 450 m and rare above 350 m.

The inhomogeneity of vesicle distribution, especially in strongly zoned pillows, makes it impractical to measure the vesicularity of the whole pillow. However vesicle counts were made on specimens from the lower halves of the pillows where inhomogeneity is less pronounced. A glass plate on which was engraved a 3 mm grid was placed on the cut surface of the specimen and centered 5 cm from the lower margin of the pillow. On each half of the specimen approximately 100 points (grid intersections) were counted, exclusive of intersections on pipes, and an average vesicle percentage obtained. While this figure is not the vesicularity of the whole pillow (being less than that value), it provides a crude measure of relative vesicularity. The graphical distribution (fig. 1, large circles), though diffuse, is consistent with the qualitative observations.

In obtaining measurements of vesicle diameters, only circular and elliptical vesicles were measured (the minor axis being measured in ellipses) since no meaningful "diameter" can be measured for vesicles of less regular form. Using a steel rule graduated to 0.5 mm, measurement was made on opposing surfaces of cut specimens from the upper

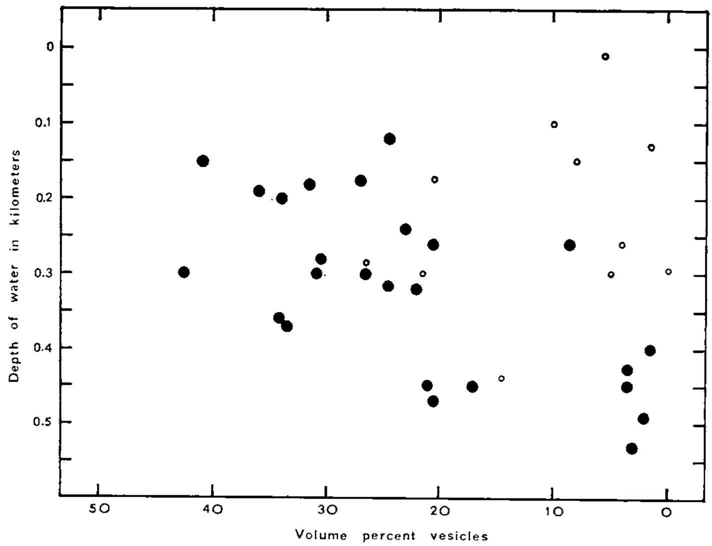


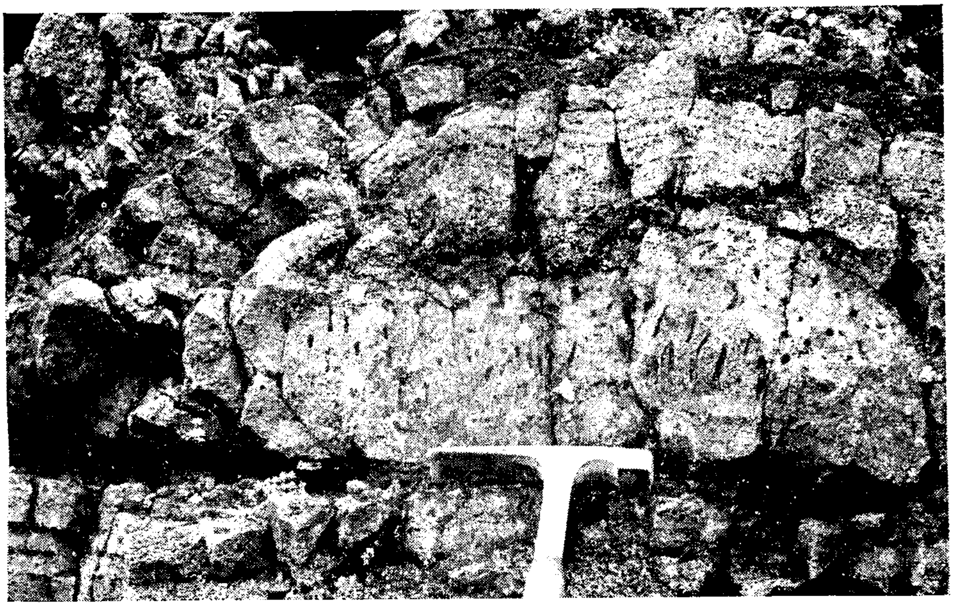
Fig. 1. Change in volume percent macrovesicles with depth for Icelandic pillow lava. Large circles, bottom of type 1 pillows; small circles, top of type 2 pillows.

PLATE 1

A.

B.

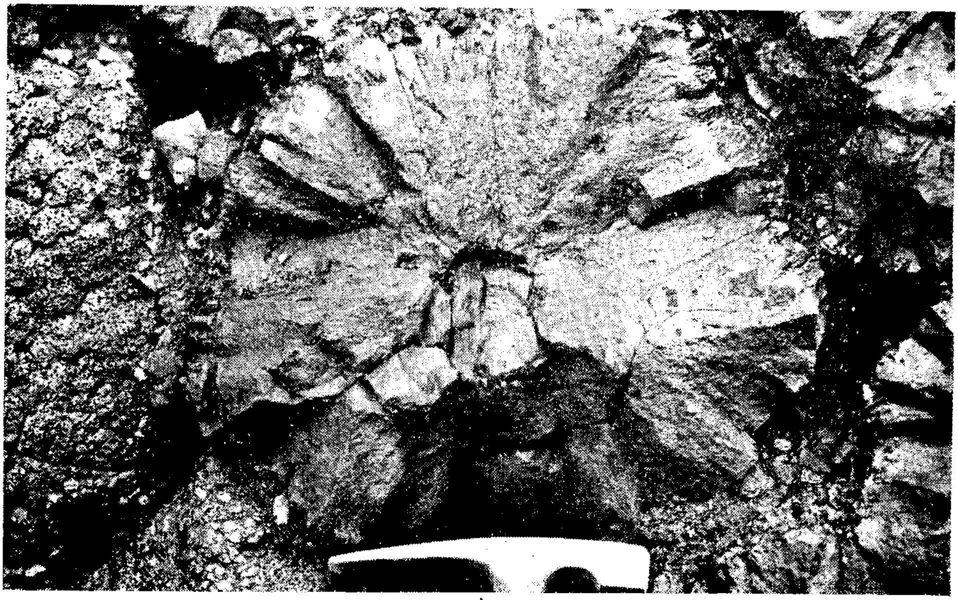
C.



D.

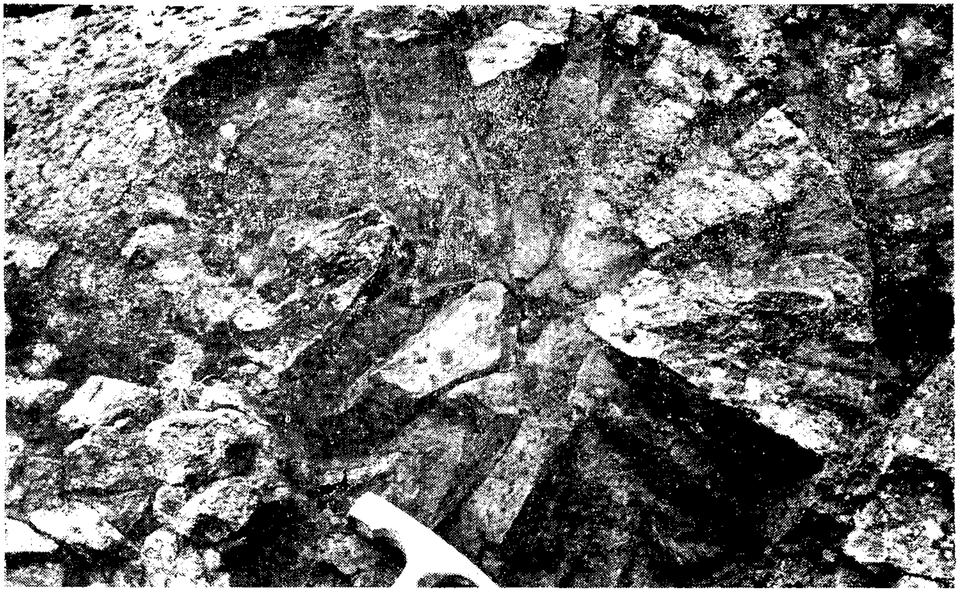
Sections of type 1 pillows, Kalfstindar, southwest Iceland: A. depth 470 m; B. depth 360 m; C. depth 300 m; D. depth 190 m.

PLATE 2



A.

B.



C.

D.

Sections of type 1 pillows, Raudafell-Hognhofdi, southwest Iceland: A. depth 530 m; B. depth 490 m; C. depth 425 m; D. depth 300 m.

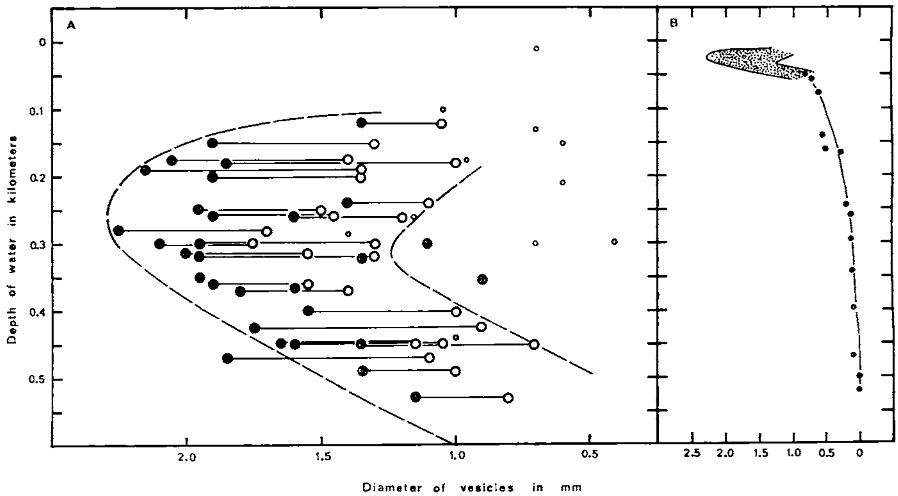


Fig. 2.A. Change in diameter of macrovesicles with depth for Icelandic pillow lava. Large filled circle, top of type 1 pillow; large open circle, bottom of type 1 pillow; small open circle, top of type 2 pillow.

B. Change in vesicle diameter with depth—synthesis of Icelandic and Hawaiian (Moore, 1965) data. Icelandic field stippled.

and lower halves of pillows. The five largest vesicles of regular form within 10 cm of the pillow margin were measured on each surface, and average vesicle diameters calculated for pillow tops and bottoms.

Figure 2A (large circles) shows the plot of vesicle diameters thus obtained. It is to be noted that vesicles are consistently smaller in the less vesicular lower halves of pillows than in the upper halves. From 550 to 300 m the vesicle diameters show a clear increase with decreasing depth. A marked decrease in the diameters of measured vesicles with decreasing depth above about 300 m is expressed in a sharp inflection of the trend (most clearly defined by the plot of bottom diameters).

Of the 10 pillow samples from depths of less than 280 m, 8 show prevalent vesicles of irregular form and/or a macroscopically perceptible but very fine vesicularity of the whole body of the pillow. Only 5 of the 20 samples below 280 m show these characters to a pronounced degree, and 2 of these are aberrant samples which plot outside the concave margin of the delineated field.

The trends of increasing vesicularity and vesicle size with decreasing depth established by Moore (1965) for the pillow lava of Hawaii reflect the response of a lava of relatively uniform composition (most importantly water content) to upwardly diminishing environmental pressure. Such presumably is the significance of the trends delineated by the Icelandic pillows, all of which are olivine basalts of very uniform character. The decrease in the diameters of measured vesicles above 300 m reflects the irregularity of form and the concomitant impracticality of measurement of many or most of the larger vesicles in these shallowest pillows. This irregularity appears to be the consequence of distortion and incomplete coalescence.

Though perceptible to the unaided eye only in some of the shallower pillows, microvesicles are visible under the microscope in type 1 pillows from all depths. They characteristically occupy interstices in the crystalline mesh. Like the macrovesicles they are larger and more irregular in pillows from shallower depths, giving these rocks a spongy microtexture akin to Fuller's (1939) "diktytaxitic" fabric. This fabric was attributed by Fuller to "the escape of the volatile constituents of the final mesostasis", and this would seem an obvious interpretation of the interstitial microvesicularity. It may well be that the distortion and coalescence of the larger and presumably earlier formed vesicles in the shallowest pillows resulted in some degree from the frothing of their matrix as a consequence of the late exsolution of volatiles from the mesostasis, a process inhibited by greater external pressure at greater depths.

The vesicle diameters as measured provide a strikingly close-fitting extension to Moore's (1965) curve (see fig. 2B). And the sharp bend of the composite curve at 500 m parallels the sharp bend of Moore's specific gravity curve.

The character of type 2 pillow lava.—Unlike type 1, type 2 pillow lava shows no depth trends in vesicularity and vesicle size but tends to contain fewer and smaller vesicles than type 1 at the same depth (figs. 1 and 2A and pl. 3-A): vesicle zoning is not encountered and interstitial microvesicles are very sparse (many fewer than in any type 1 pillow) or absent. Yet there is no indication of any significant compositional difference between type 2 and type 1 pillow lava[2].

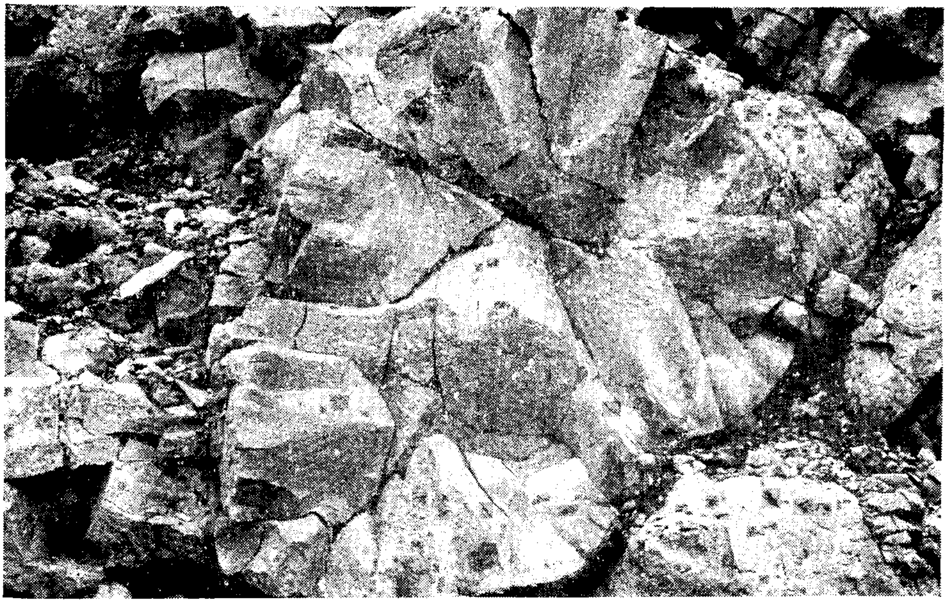
The key to the differences is to be found, I believe, in the different stratigraphic environments of the two types. Type 1 constitutes the basal pillow lava piles of Kalfstindar and Raudafell-Hognhofdi and records a phase of effusion of lava in water that preceded emergence (Jones, 1966; 1968). Type 2 pillow lava on the other hand is closely associated with the tuffs and flow-foot breccias produced during and after emergence of Raudafell-Hognhofdi from the meltwater lake. Some type 2 pillow lava is almost certainly the product of immersion of lava flows extruded at the emergent summit vents. Most, I suspect, is the product of eruptions on the submerged flanks of the emerged volcano. This supposition is supported by the presence of a number of small conical mounds on the flanks of Raudafell-Hognhofdi which consist of type 2 pillow lava and are very suggestive of accumulations at parasitic vents.

The characteristics of type 2 pillow lava can be readily explained in terms of partial degassing of the lava at the emergent summit, accompanied and followed either by extrusion and subsequent immersion of lava flows or by backflow and reemergence of lava on the submerged

[2] Atomic absorption analyses of Icelandic pillow lavas. Analyst, A. J. Thompson, Imperial College, London.

	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2
type 1 (Kalfstindar)	16.2	12.3	10.6	12.5	2.5	0.2	1.3
type 2 (Raudafell)	15.8	12 4	10.5	12.3	2.5	0.4	1.4

PLATE 3



A.

B.

C.

D.

A. Section of type 2 pillow, Hognofdi, southwest Iceland; depth 130 m. B, C. D. Sections of pillows, Strumble Head, Wales; B. base of sequence; C. upper middle of sequence; D. top of sequence.

flanks (summit eruption followed by backflow and flank eruption is common in Hawaii; see for instance Richter and others, 1964). The relatively low volatile content of the lava at the time of pillow formation is reflected in the relative paucity and small size of vesicles and the virtual absence of interstitial microvesicles at even the shallowest depths. The apparent lack of any correlations with depth would be expected in terms of variable degassing.

Evidence of a feeble recurrence of eruption on Hognhofdi at a higher stand of water level (Jones, in prep.) introduces a complicating factor into discussion of the genesis of the type 2 pillow lava, some of which might be the product of this phase of activity. Thus the possibility must be considered that the vesicularity differences between type 1 and type 2 pillow lava at any one level reflect different water levels during their periods of eruption. However, if it is assumed that all type 2 pillow lava is the product of the final eruptive phase and the depths are adjusted accordingly, those type 2 vesicle diameters that lie outside the field of type 1 pillows in figure 2 remain outside. Furthermore, it must be born in mind that the differences between type 1 and type 2 pillows are not simply differences in size and number of vesicles that might be accounted for in terms of depth of water. Type 2 pillow lava, unlike type 1, shows no depth trends in vesicle size and abundance and differs perceptibly in texture and color though not in composition. Thus degassing of lava at an emergent vent prior to pillow formation remains the most satisfactory explanation of the type 2/type 1 difference.

PILLOW LAVAS OF STRUMBLE HEAD, WALES

Ordovician pillow lava is superbly exposed in the vicinity of Strumble Head, Pembrokeshire, and a 4-km stretch of coastline southwest of Strumble Head has been examined in detail. The rocks dip north-northwest to north-northeast at angles from 35° to 70° (see fig. 3). They are closely block faulted, the largest detected displacement being about 75 m. A number of small repetitions of sequence are a consequence of this faulting. The lower part of the sequence consists very largely of pillow lava with subsidiary pillow breccia. The upper part consists very largely of non-pillowed lava, mostly in units tens of meters thick and less commonly in tabular units up to several meters thick with abrupt rounded ends, closely associated with pillow lava. Thin, well-bedded sedimentary partings occur at all levels in the sequence, though more prominently toward the top.

Unfortunately the closely spaced faults and the difficulty of detecting the direction and magnitude of displacements make it impossible to determine the stratigraphic positions of the sampled pillows with any semblance of accuracy. A crude approximation of relative stratigraphic positions has been derived by the means shown in figure 3. Bearing in mind repetition by faulting, the thickness of the sequence is unlikely to exceed 1500 m (the thickness of an unfaulted sequence dipping north at 50°).

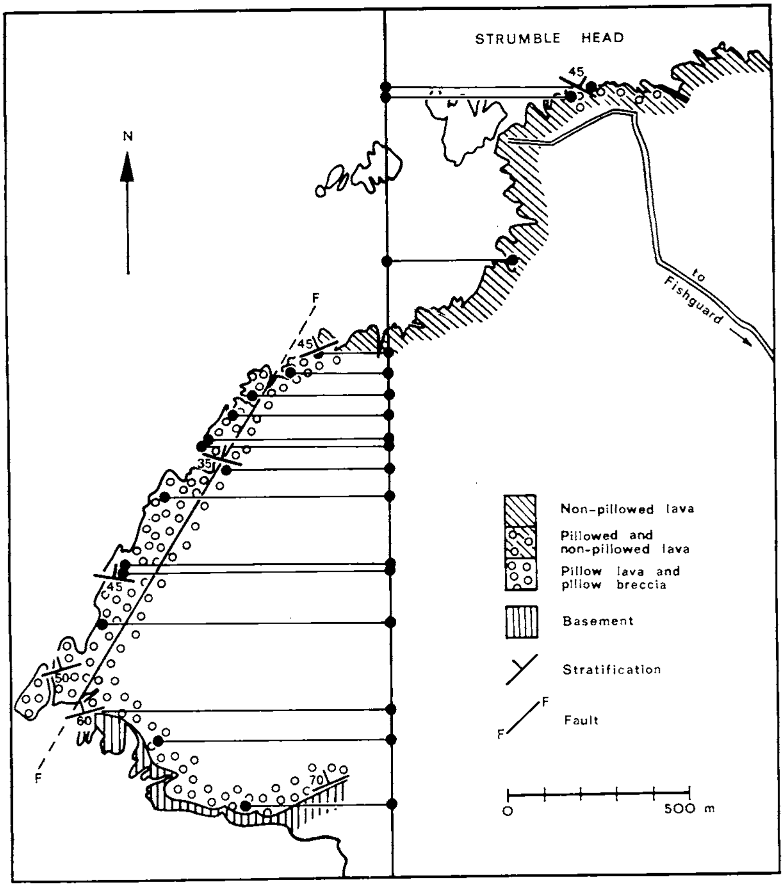


Fig. 3. Map of Strumble Head (Wales) coast section showing location of pillow samples (filled circles) and mode of approximation of relative stratigraphic position.

Figures 4 and 5 record the volume percent and the diameter of macrovesicles in the Strumble Head pillows, plotted against their approximate stratigraphic position. The methods of measurement are the same as for the Icelandic pillows[3]. These graphs reveal an unmistakable though diffuse pattern of up-sequence increase in the abundance and size of macrovesicles. Plate 3-B, C, and D portray the character of this variation as seen in the field, though with the oversimplification that selection necessitates.

What can be inferred from the size and abundance of macrovesicles in the pillow lava of the Strumble Head sequence on the basis of the Hawaiian-Icelandic data? The trends of up-sequence increase in the abundance and size of macrovesicles indicate that pillow lavas at the

[3] In measuring vesicularity five specimens were rejected because the indistinctness of the macrovesicles on the cut surface rendered the method of measurement inadequate.

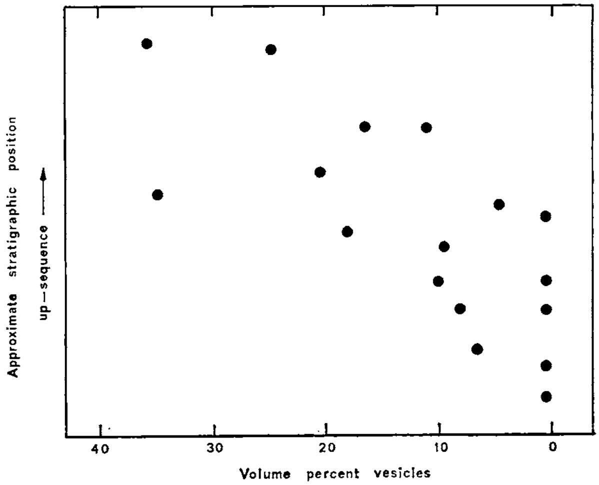


Fig. 4. Change in volume percent macrovesicles with stratigraphic position for Welsh pillow lava. Samples from top of pillows.

base of the sequence were emplaced in water appreciably deeper than pillow lavas toward the top of the sequence. The values suggest neritic-bathyal (0-2000 m) rather than abyssal depths. Pillow lava near the top of the sequence displaying abundant, irregular, conspicuously zoned macrovesicles (pl. 3-D) and a microvesicularity perceptible to the unaided eye may have been emplaced in water no more than a few hundred meters and possibly tens of meters in depth.

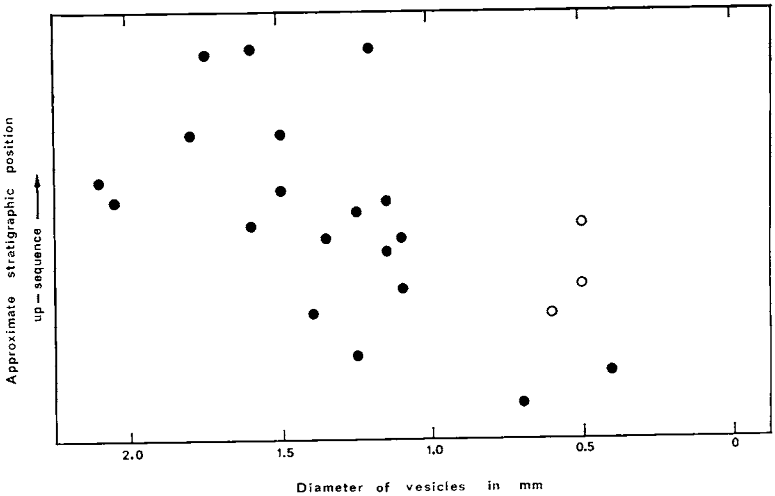


Fig. 5. Change in diameter of macrovesicles with stratigraphic position for Welsh pillow lava. Open circles denote samples in which less than ten vesicles measured. Samples from top of pillows.

ADDENDUM—SIGNIFICANCE OF SEGREGATION VESICLES

Vesicles in basalt lava lined with dark fine-grained material believed to represent residual melt have been termed "segregation vesicles" by Smith (1967). Smith proposes the interesting hypothesis that such vesicle infilling may result from increased confining pressure on a subaqueous lava flow moving into progressively deeper water. However it seems to me unlikely that the lava would continue to flow freely after the formation of "a relatively rigid framework of crystals" as the hypothesis requires. Segregation vesicles are extremely common in Icelandic pillow lavas but show no perceptible variation in development with depth. For the Icelandic pillow lavas at least, it seems to me more probable that the expulsion of residual liquid into early-formed macrovesicles occurred during later vesiculation of the mesostasis with the formation of the prevalent interstitial microvesicles, some time after the lava had ceased to flow.

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