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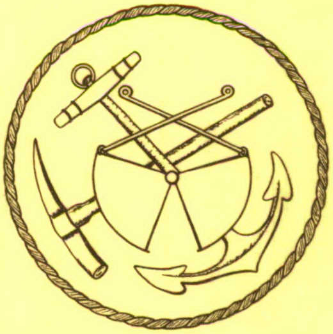

DEPARTMENT OF GEOLOGY

FLORIDA STATE UNIVERSITY

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PETROLOGIC VARIATIONS WITHIN SUBMARINE BASALT PILLOWS OF THE SOUTH PACIFIC-ANTARCTIC OCEAN

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ABSTRACT

The chemistry of submarine basalts has been used in upper mantle petrogenesis models but criteria for selecting fresh, representative samples and an understanding of within-specimen variations are vague. In an effort to define alteration criteria, variations in the mineralogical, chemical and magnetic parameters of one alkalic and eight tholeiitic basalt pillows from abyssal hills in eight widely scattered localities of the Southern Ocean have been studied from glass rim to aphanitic interior. These variations are related to primary cooling (quenching and deuteric alteration) and secondary alteration (hydration and recrystallization).

Four texturally gradational zones are defined from glass rim inward: hydrated glass, unhydrated glass, "variolitic" zone, and aphanitic zone. This transition occurs through a minimum thickness of three centimeters. These zones are also characterized by low intensity of magnetization (J) and low susceptibility (c.g.s. units) in the glass (no opaques), high J and susceptibility in the variolitic zone (very minute opaques), and medium J and susceptibility in the aphanitic basalt (opaques larger than single domain size). Deuteric alteration affects the intensity and coercivity of the basalts. Vesicularity in the eight tholeiites does not exceed 3% at depths greater than 3200 meters which is consistent with physico-chemical data.

Three types of alteration are common; (1) glass hydration (>2.0% total H_2O) resulting in loss of magnesium and calcium and increase of total iron, ferric/ferrous ratio, and potassium; (2) serpentinization adjacent to joints and fractures; and (3) higher temperature deuteric alteration in the aphanitic zone causing depletion of magnesium and total iron as FeO (up to 2.0 wt. percent of rock). The iron migrates to joints where it is oxidized and made available in significant quantities for redeposition in iron-rich sediments and ferro-manganese concretions.

It is concluded that the unhydrated glass and variolitic zones are most representative of the pillows' chemical compositions which are slightly undersaturated tholeiites. Alteration of one pillow greatly affects its composition whereas seven of the tholeiites which are relatively unaltered lie within a normative compositional range of Ab, 22.5-24.1%; An, 23.5-30.0%; Di, 19.2-24.6%; Ol, 0.6-4.5%; Hy, 14.6-19.5%.

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INTRODUCTION

The chemical characteristics of oceanic basalts have an important bearing on any possible sequence of differentiation among the various basalt types because contamination from continental crust is minimal in the ocean basins. In as much as the chemistry of oceanic basalts is relatively uniform, surprisingly so in view of their areal extent, they are believed to reflect the chemical characteristics of the earth's upper mantle (Engel, Engel, and Havens, 1965). However, the extent of post-eruptive chemical alterations in submarine basalts is not known and interpretations concerning the composition of the parental mantle material based on altered basalts could be significantly in error.

Further, the alteration of submarine basalt has been postulated to be an important source of the metal ions which comprise marine ferro-manganese concretions (Bonatti and Nayudu, 1965). No definitive chemical or mineralogical data on the basalts themselves have as yet been presented which could serve as direct evidence bearing on this hypothesis.

Two modes of submarine volcanism have been reviewed by Menard (1964): tranquil flow with the formation of pillow lavas, and explosive emanations with the formation of ash.

Both have been observed in shallow water but their relative importance has not been established at abyssal depths. Pillow lavas can be recognized in bottom photographs, but explosion ash cannot be similarly distinguished from other sediments.

Bonatti (1965, 1967) believed that explosive emanation is substantial at abyssal depths based on the abundance of glass fragments and their abnormally high hydration rate compared to continental glass shards. He believed this discrepancy can be explained only by the interaction of hot, explosive emanations with sea water.

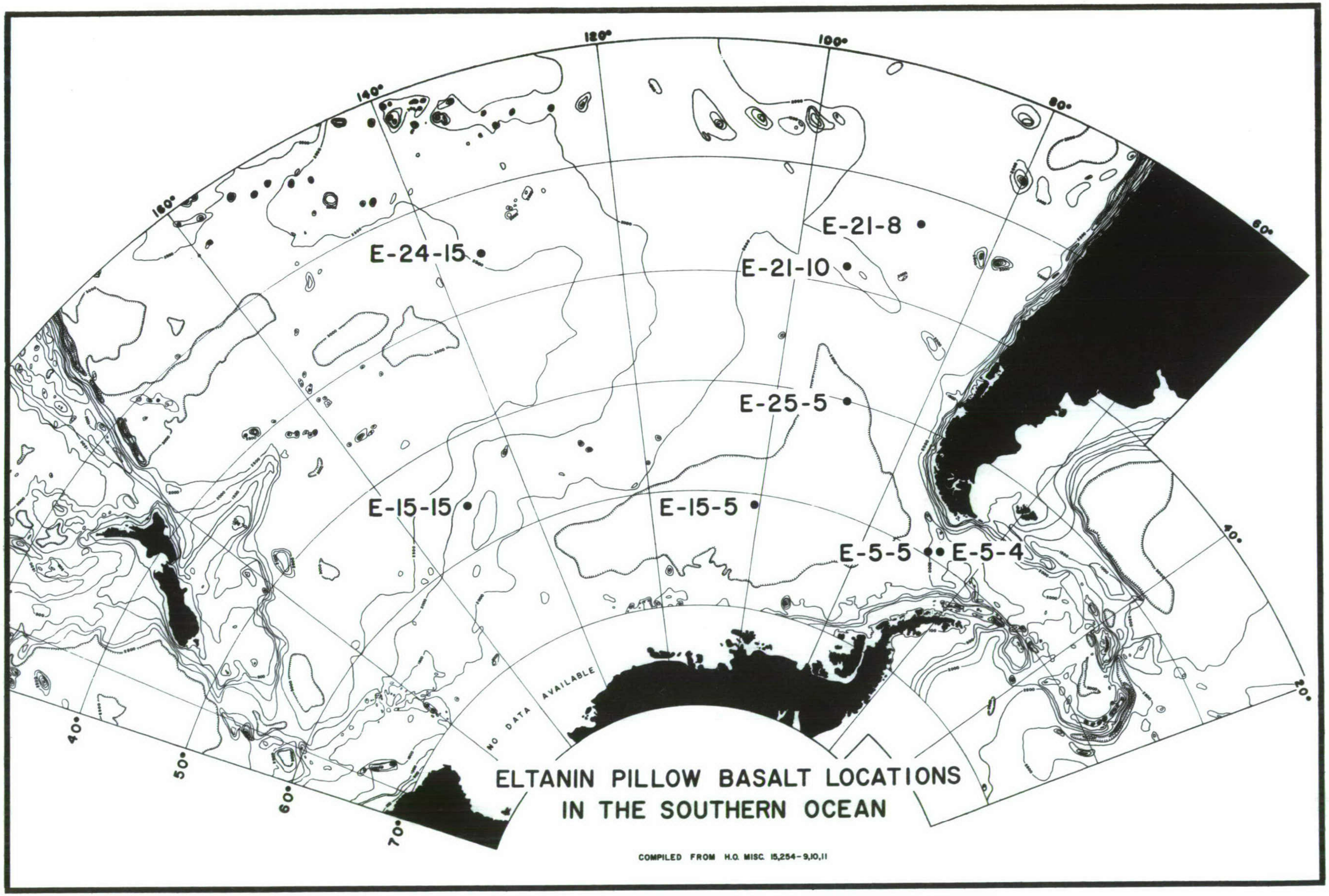
Bonatti (1967) postulated that the only fundamental difference between the two types of eruption is the viscosity of the lava upon contact with sea water; low viscosity results in tranquil flow, high viscosity results in "explosive" glass fragments. He reasoned that the principle factor in determining the viscosity of the lava is the gas content of the molten lava, higher gas contents resulting in lower viscosities. The glass rims of the Southern Ocean pillow fragments were examined for cooling effects which may have a bearing on the relative importance of the two modes of eruption.

Physico-chemical considerations of the behavior of water in basaltic melts at abyssal depths are not consistent with some reports of abyssal submarine basalts containing voids or high concentrations of vesicles. Pillows are more amenable in studying this problem because there is relatively little time for excess water to be introduced into the hot lava before it solidifies. Water is one of the most important constituents which could significantly alter the vesicle content of submarine basalts at depth.

The natural remnant magnetism of submarine basalt is of interest not only in aiding interpretations of the magnetic character of the ocean floor but also in understanding the nature of the remnant magnetism itself. The variations of magnetic mineral size and the oxidation state of the iron are sufficient in pillows to compare their effects with the general magnetic properties of the rock. Unfortunately, texture in pillows is generally too fine-grained to be of use in studying attendant variations among the opaque minerals.

In view of the uncertainties concerning the extent of post-eruptive alteration nine pillows dredged by the USNS Eltanin from eight widely separated Southern Ocean localities were investigated chemically and mineralogically for variations within single fragments and to describe the nature and extent of alteration. Basalt E-5-4 is from a rise in the Drake Passage as is E-5-5, the only sample obtained from a seamount. E-21-10-1 and E-21-10-2 are from the Chile Rise (Figure 1, Table 1). The rest of the pillows have been dredged from abyssal hills. All of the basalts but E-5-5 are from depths ranging between 3200 and 4800 meters. With the

Figure 1- Location Map of *Eltanin* Pillow Basalts



ELTANIN PILLOW BASALT LOCATIONS IN THE SOUTHERN OCEAN

COMPILED FROM H.O. MISC. 15,254-9,10,11

TABLE 1

LOCATION, DEPTH, AND REMARKS ON SAMPLE SITES

Sample Number	Latitude		Longitude		Depth (meters)	Remarks
E- 5- 4	59°02'	S	67°15'	W	3475	Scotia Ridge, 180 meters relief.
E- 5- 5	59°45.5'	S	68°50'	W	1372	North slope of unnamed seamount.
E-15- 5	61°06'	S	104°58'	W	4828	Flat bottom.
E-15-15	56°02'	S	149°40.9'	W	3256	Abyssal hills, 390 meters relief.
E-21- 8	32°58'	S	87°59'	W	3621	Rolling terrain, 55-70 meters relief.
E-21-10, 1 & 2	37°19'	S	94°39'	W	3292	Rugged hills on crest of Chile Rise, 550 meters relief.
E-24-15	35°58'	S	134°50'	W	4682	Undulating bottom, 20-90 meters relief.
E-25- 5	49°57'	S	89°59'	W	4280	Undulating bottom, 550 meters relief.

exception of E-5-5 the basalts represent samples from localities dredged with no specific physiographic or geologic target in mind and therefore may be representative of submarine flows on the deep ocean floor.

The data presented herein should provide firmer criteria for establishing whether or not a particular analysis is representative of a particular submarine basalt fragment and so allow it to be used in general petrogenetic theory. In addition, the characterization of alteration in submarine basalts might be related to the source problem of elements in ferro-manganese concretions.

PREVIOUS WORK

General Petrology

The chemical composition of tholeiite as originally defined is now only a point within the chemical range of what is presently considered a rock type. Thus, strictly speaking, most rocks which are considered tholeiites do not correspond in composition to the classical tholeiite. As a result of the indiscriminate use of this term, much confusion has arisen as to its meaning (Tilley and Muir, 1967). If the term is recognized only as a name which is applied to a rock and magma type (Tilley and Muir, 1967) within the basalt clan which has a finite range in chemical composition and which can be recognized as a discrete petrological entity (Macdonald and Katsura, 1964), then the term is useful. Because the majority of tholeiites described is from the continental environment, further confusion may ensue when the term is applied to oceanic rocks, for here there is a distinctive rock type which has been called "oceanic tholeiite" (Engel et al., 1965), but whose chemistry differs from what has come to be known as tholeiite. The difference between the two tholeiites is slight, but significant enough to set oceanic tholeiite apart from tholeiite of the continental environment. This difference is primarily a lower potassium percentage in oceanic tholeiite. About .20 per cent K_2O is found in oceanic tholeiites while continental tholeiites contain upward of .50 per cent K_2O. There is, in addition, a transitional tholeiite which has an intermediate potash percentage and this tholeiite is found principally on oceanic islands such as Hawaii (Macdonald and Katsura, 1964). The present paper will refer to oceanic tholeiites as tholeiites for brevity, although there may be justification for setting these two tholeiites apart.

The petrographic classification used in this paper is taken from that of Macdonald and Katsura (1964, p. 88-89). Accordingly, the most common basalts found in oceanic regions are tholeiites, olivine tholeiites and alkalic basalts. Tholeiites are rocks saturated in silica in which magnesian olivine reacts with the melt to form calcium-poor pyroxene (Kennedy, 1933; Tilley, 1950). Olivine tholeiite contains more than 5% modal olivine whereas tholeiite contains less than 5%. Alkalic basalts are generally similar in composition to tholeiites and olivine tholeiites, their principal difference being an enrichment in total alkalis.

In general, the groundmass pyroxene of tholeiites is pigeonite with augite whereas that of alkalic basalts is augite alone. The augite of alkalic basalt may exhibit a small positive optive angle like that of pigeonite, however, this is believed to be due to an iron- or titanium-rich variety of augite since the augite is often distinctly purplish with strongly inclined dispersion, characteristics commonly assigned to titanaugite (Muir and Tilley, 1961). The composition of the plagioclase, an essential mineral in basalts, is near An_{50} in tholeiites and is generally more calcic than An_{50} in alkalic basalts. Groundmass olivine is usually taken as evidence that a basalt is alkalic.

Many petrologists designate olivine tholeiite as the primitive magma from which tholeiite is derived through fractional crystallization and from which alkalic basalt is produced by either fractional crystallization, gaseous transfer, or assimilation. Powers (1955) objected to the premise that alkalic basalt could be derived from tholeiitic basalt by fractional crystallization on the grounds that either removal or addition of olivine, hypersthene, augite and plagioclase to either of these two rock types results in an excess or lack of free silica in the difference. Free silica must be added to alkalic basalt or subtracted from tholeiitic basalt to match the two compositions. Yoder and Tilley (1962, p. 410) have discussed the alkali basalt problem from the experimental viewpoint and agree that alkalic basalt cannot be generated from an olivine tholeiite through removal of olivine. They conclude that alkali basalt magmas are derived from greater depths in the mantle than tholeiitic magmas (p. 509).

Photographs of submarine lava flows have been taken on the flanks of Hawaii (Moore and Reed, 1963), on the East Pacific Rise (Bonatti, 1967; Engel and Engel, 1964), and on the Mid-Atlantic Ridge (Muir, Tilley, and Scoon, 1964). Flows in many parts of the Southern Ocean have been photographed by the USNS Eltanin (Goodell, 1964, 1965, 1968). The pillows are generally bulbous in shape with diameters ranging from 5 to 60 cm. Dredge hauls of pillows yield roughly wedge-shaped, angular slabs or blocks of basalt which are a product of columnar jointing perpendicular to the pillow surfaces.

The distance between joints ranges from 2 to 15 cm. The blocks are composed of glass and aphanitic basalt; one end is usually convex or concave being comprised of a dark rim of basaltic glass from 0.1 to 2.0 cm. thick. The glass surfaces may be hydrated to a reddish-orange to buff layer of palagonite (hydrated glass) up to 2 mm. in thickness. The glass surfaces of some pillows have been reported to show traces of pahoehoe ropy structure. The pillows may be vesicular, non-vesicular or contain a concentration of vesicles beneath the glass rim. Vesicles beneath the glass rim have been reported to have coalesced into a nearly continuous cavity (Moore, 1965; Bonatti, 1967).

Evidence has been cited which indicates that submarine lavas upon extrusion are in some cases more fluid than subaerial lavas. Engel and Engel (1964) reported that one thin edge of a pillow formed a cast of ripple-marked sediment over which it flowed and submarine flows of only 10 cm. in thickness have been noted (Bonatti, personal communication). Macdonald (1968, p. 26) stated that the fluid interiors of some pillows have drained leaving cavities and he discussed the genetic relationship among pahoehoe toes (terminal tongue-shaped protrusions of solidified pahoehoe), pillows, and angular glass fragments (hyaloclasts) and demonstrated that all of these products could be produced from the pahoehoe flows of the tranquil type of submarine eruption. Bailey, Irwin, and Jones (1964, p. 51) have reported hyaloclast concentrations of 50% intermixed with the smaller pillows of the Franciscan Formation.

Vesicularity of Submarine Lavas

The role of water in the development of vesicles in basaltic lava at the temperatures and pressures involved at abyssal depths has been discussed in detail by Menard (1964), Rittman (1962), and McBirney (1963). From the experimental data of Kennedy (1950), it can be shown that water vapor at pressures of 100 to 500 atmospheres (approximately 1000 to 5000 meters water depth) and a temperature of 1000°C rapidly rising from a depth of 3510 meters in a volcanic fissure to 3500 meters on the ocean floor will expand only about 2 per cent with this sudden pressure decrease. Water vapor at the same temperature and rising at the same rate in a volcanic pipe from 10 meters below sea level to sea level with the same sudden pressure decrease, will expand 1000 per cent. As a result, a basaltic lava slightly oversaturated with as much as two per cent total water will not vesiculate to more than a few per cent by volume upon eruption below 2000 meters water depth.

All other things equal, the volume per cent vesicles should be dependent upon water depth. Other gases, of course, are not considered and if the lava is appreciably oversaturated in volatiles at the time of quenching a higher vesicle percentage may be expected. Moore (1965) substantiated this relationship by plotting the volume per cent vesicles in pillows recovered near Hawaii versus water depth and found an inverse relationship. Because the water in molten lava expands only slightly upon release of pressure at abyssal depths "pulverized" glass (hyaloclasts) is the dominant volcanic ash constituent at depth in contrast to ash formed under less confining pressure which usually contains the familiar shards formed by the fracturing of glass walls of gas bubbles.

Petrography of Pillows

Textures in submarine basalts are as variable as in subaerial basalts with the exception of pillows, whose texture and mineralogy have been described in some detail by Moore (1966). He divides the textural variations from the outer quenched glass surface to the interior of pillows into six layers:

1. A black manganese mineral coating up to 1 mm. in thickness.
2. A yellowish brown palagonite layer up to 0.7 mm. thick with minute botryoidal banding convex in detail toward the inner part of the pillow. The banding may be extremely fine and parallel layers as thin as 1 micron can be identified on the inner 1-mm-thick palagonite rinds. The palagonite is in sharp contact with the glass and near the contact it is generally pale yellowish to almost white and distinctly lighter in color than the pale-brown glass it replaces. Outward from the center of the pillow, the palagonite becomes darker yellow-brown and minutely granular in texture and darker than the glass it replaces.
3. A transparent light-brown glass up to 10 mm. thick which commonly contains phenocrysts and a few microlites.
4. Speckled brown glass up to 10 mm. in thickness which is transitional between layers 3 and 5. Scattered black, opaque areas occur in the transparent glass. These spots are fine feathery and dendritic crystallites.

5. Black opaque "glass" about 10 mm. thick which is transitional to layer 6.
6. Aphanitic basalt which makes up most of the interior of the pillow.

The opaque "glass" layer has been variously termed by previous authors as devitrified glass, semi-opaque matter, or sideromelane.

Alterations

A number of alterations are common in pillows. These include hydration (palagonitization) and zeolitization of basaltic glass and deuteric alteration of olivine and pyroxene to such secondary minerals as chlorite, serpentine, talc, goethite, and hematite.

Some types of alteration reported earlier (Matthews, 1962), are suspect since more recent comprehensive investigations indicate that alteration of crystalline basalt to clay minerals is restricted almost entirely to seamounts, banks, and guyots which may have been exposed to conditions approximating subaerial weathering (Bonatti, 1967; Moore, 1965, 1966; Rex, 1967).

Investigations of numerous samples of submarine basalt from all parts of the ocean floor suggest that spilitization of basalt on the ocean floor is rare (Engel, Fischer, and Engel, 1965; Bonatti, 1967) and restricted to the oceanic ridge system where processes of metasomatism appear to be significant (Melson and Van Andel, 1966). There appears to be no evidence that calcic plagioclase is converted to sodium feldspar through direct contact of basalt with sea water, either when freshly erupted or when exposed for considerable lengths of time at sea floor temperatures. Many submarine basalt descriptions, especially those of pillows, include a statement of the remarkably fresh appearance of the feldspars.

Hydration is the first observed stage in secondary alteration which volcanic glass undergoes short of high temperature metamorphism (Marshall, 1961; Hawkins and Roy, 1963). It is also clear that glass hydration proceeds at significantly faster rates than does the alteration of most of the associated minerals. Because devitrification of anhydrous glass is an extremely slow process and would not be found in even the oldest rocks of the ocean floor (Marshall, 1961), the common secondary minerals of basaltic glass (i.e., montmorillonite and phillipsite) are formed only after the glass has been hydrated.

Moore (1966) presented evidence that the palagonitization of basaltic glass during initial cooling of the lava is relatively insignificant ($\sim$2 microns in thickness) and found a correlation between the thickness of the hydrated glass layer and the ages of the basalts. His results indicated a much higher rate of hydration for basaltic glass than for silica-rich glass. Experimental studies by Hawkins and Roy (1963) showed that the concentration of magnesium in both glass and the aqueous environment was a dominant factor in the rate of alteration. Where the magnesium content of the weathering solution is comparatively low, as in the case of sea water, the amount of silica and magnesium in the glass plays a greater role in alteration with the rate proceeding more rapidly in a glass of high magnesium and low silica content. The reduced rate of alteration in a magnesium-deficient water might explain why Moore found lower rates of hydration of basaltic glass in a fresh-water lake as compared to those in sea water.

There are few available data suggesting what per cent water is necessary before a basaltic glass may be considered hydrated. Ten hydrated-nonhydrated silicic glass pairs studied by Noble (1967) include a water content of less than 0.5% for the nonhydrated glass. Ross and Smith (1955) give a value of 0.9% water content for unhydrated obsidian. The highest value for unhydrated glass of basaltic composition is given by Correns (1930) who reported a value of 1.22%.

A number of analyses of hydrated glasses have been made in order to determine what chemical changes are attendant upon hydration. Most of these have been made on silicic glasses, a few on hydrated-nonhydrated basaltic glass pairs. The results, though tentative, indicate that chemical changes in the two types of glass are the same qualitiatively.

Nicholls (1963) found a decrease in the percentage of calcium, magnesium, and sodium in hydrated basaltic glass and attributed the losses to leaching by sea water. Noble (1967) found an increase in potassium in hydrated silicic glass relative to unhydrated glass and interpreted the gain as an ion-exchange interaction between the glass and the hydrating water. An increase in total iron and ferric/ferrous ratio in hydrated basaltic glass relative to unhydrated glass has been reported by Nicholls (1965) and Bonatti (1965). Noble (1967) suggested that aluminum is relatively immobile during hydration while silicon may be lost.

The deuteric minerals reported to be in submarine basalts are: chlorite, calcite, iddingsite, serpentine, quartz and hematite (Quon and Ehlers, 1963); iddingsite, chlorite and iron oxides (Engel and Engel, 1963); iddingsitic material, spongy iron hydroxide, bright-green chlorite, olive-colored chlorite, yellow-brown chloraphaeite, fibrous zeolites, calcite, greenish decomposition products (Shand, 1949); olive-colored serpentine, serpentinized olivine, hematite, clay minerals, chlorite, serpentine-talc aggregates, and hydrated iron oxide stains (Poldervaart and Green, 1965); and green, fibrous serpentine (Muir, Tilley, and Scoon, 1964). These alteration products are commonly found in dolerites and diabases as well as in trace amounts in pillows.

Magnetic Properties

No studies of the magnetic variations in submarine pillows have as yet been published. Ozima, Ozima, and Kaueoka (1968) have done some work on basalt fragments but not all of these were pillows nor were the variations within fragments studied. The relatively high ferrous/ferric ratios in such rocks suggest that their magnetic properties should be due to the relatively unoxidized ülvospinel-magnetite solid solution series and the cooling history of the pillows.

Havard and Lewis (1965) have described partial thermoremnant magnetism (PTRM) in the ülvospinel-magnetite solid solution series of some Indian lavas and have shown that reverse PTRM occurs in this series due to a state of partial oxidation of the titano-magnetite. They found that fully oxidized titano-magnetite has a high temperature component (A) and partially oxidized titano-magnetite has, in addition to (A), a low temperature component (B) which is oppositely magnetized to the direction of (A) and coupled to it by a weak magnetic interaction. Unoxidized or fully oxidized material has normal PTRM and partially oxidized material has reverse PTRM. These data are similar to those from certain ilmeno-hematite minerals (Carmichael, 1961).

PROCEDURES

Samples

Basaltic pillows have been chosen for this investigation for a number of reasons: (1) fragments of pillows are easily recognized megascopically and may therefore be selected from dredge hauls which may contain ice-rafted debris, (2) pillows contain glass which is believed to be the most representative material of the original basaltic melt, (3) these fragments are a common material from the deep ocean floor, and (4) direct chemical interaction of hot lava with sea water would be optimal in pillows.

Petrography

Thin sections cut normal to the pillow surfaces and polished thin sections cut parallel to the glass surfaces at intervals from the surface to the interior of the pillows were prepared and examined under a polarizing and reflection microscope by conventional techniques. Where mineral or vesicle percentages are reported the values are based on a minimum of 2,000 point counts on a grid pattern of 3.5 points per mm. The fine-grained texture of the material allowed such a closely spaced grid without two consecutive points falling on a single crystal with the exception of relatively large phenocrysts. The identification of minerals in joints and hydrated glass was supplemented by X-ray diffraction.

Chemistry

Each of the nine pillow fragments was sampled in at least two of the four pillow zones for chemical analysis. Twenty-five complete and two partial major element analyses were performed in duplicate with the exceptions of H_2O^+, H_2O^- and FeO which were performed only once on each sample. The method of analysis used for most elements has been outlined by Shapiro (1967). SiO_2 and Al_2O_3 were determined by NaOH fusion in a nickle crucible as outlined by Shapiro and Brannock (1962). FeO was determined by the method of Reichen and Fahey (1962) which consists of oxidizing the powdered samples with $K_2Cr_2O_7$ in the presence of HF and H_2SO_4 then titrating the excess dichromate. The water determinations were made using the method of Shapiro and Brannock (1962).

Where determinations in duplicate were made, they have been averaged. Standard basalt W-1 was used as a standard for most constituents.

Magnetic Measurements

The basalt fragments were cored normal to their glass rims and the 2.5 cm. diameter cores were cut into 2.0 - 2.5 cm. lengths. The intensity of the natural remnant magnetism (J) of the samples was measured on an astatic magnetometer (constructed by N. D. Watkins) before and after demagnetizing the samples in alternating fields of progressively increasing magnetic intensity (H). In this way variations in J and magnetic stability of the basalts with depth in the pillows were obtained. The magnetic susceptibilities were also measured using a susceptibility bridge (Collinson, Molyneux, and Stone, 1963) calibrated with salts and rocks of known susceptibility.

RESULTS

Megascopic description of pillows

Most of the Eltanin basalts are angular blocks characteristic of jointed pillow fragments generally 8x10x15 cm. in size and therefore much larger than the fragments described by Moore (1965). Joint surfaces of the pillow blocks are commonly coated with goethite. The glass surfaces of the blocks do not display obvious pahoehoe structure.

Two basalt fragments of this study are in the shape of "toes" approximately 30 cm. in length which taper to about 5 cm. at their termini (Plate 1a).

The Eltanin pillows contain less than 3 per cent vesicles and exhibit no concentration of vesicles within them with the exception of toe E-5-4 (Plate 1b) which contains a large central cavity. E-5-5 averages 37% vesicles in the 19 cm. next to its glass surface and 13% vesicles below this zone (Fig. 2).

Pahoehoe toes E-5-4 and E-24-15 contain many more concentric fractures in their glassy rims than do the rims of the larger pillows. These concentric fractures are unevenly spaced and are connected at irregular intervals by radial fractures (Plates 1c, 1d).

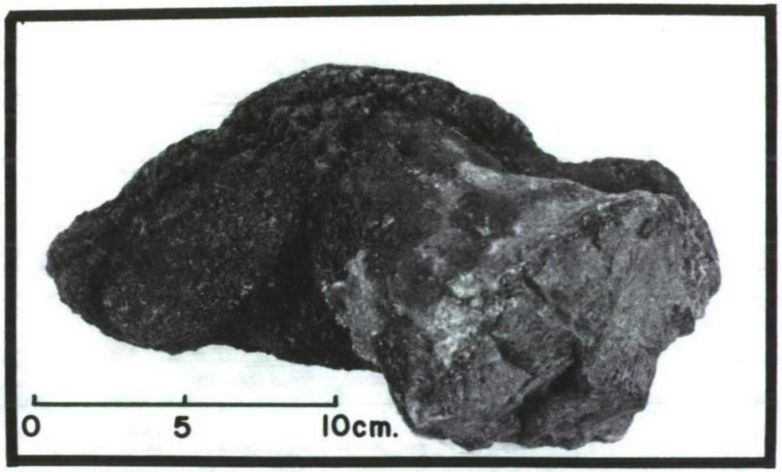
Plate 1.

a. Pahoehoe Toe E-24-15 with a ferro-manganese crust from 1.0 to 1.4 cm. thick.

b. Sections Through Toe E-5-4 showing central cavity and concentric fractures in glass rim filled with phillipsite.

c. Thin Section Through Toe E-24-15 showing concentric fractures lined with palagonite and phillipsite. Note thick palagonite rim preserved at top and left edge of pillow which is lighter in color than unhydrated glass.

d. Fractured Rim of Toe E-24-15 with a few scattered vesicles and agglomerates of olivine and plagioclase rimmed with incipient, variolitic pyroxene set in a clear light brown glass.



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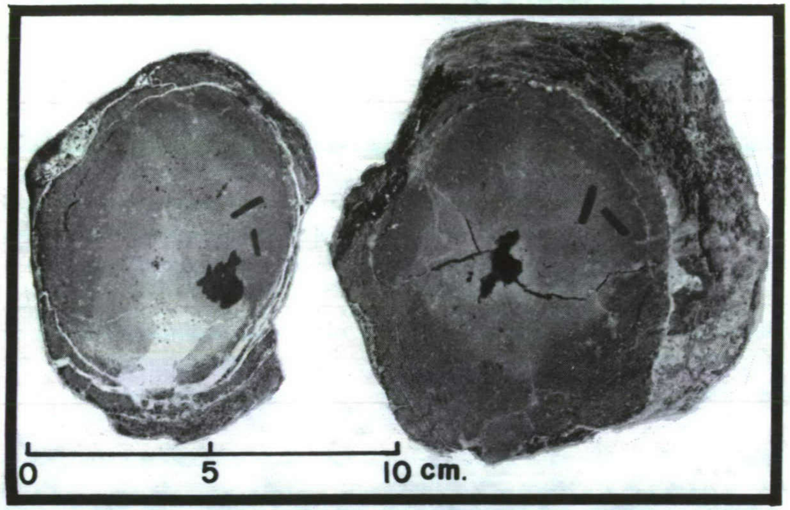

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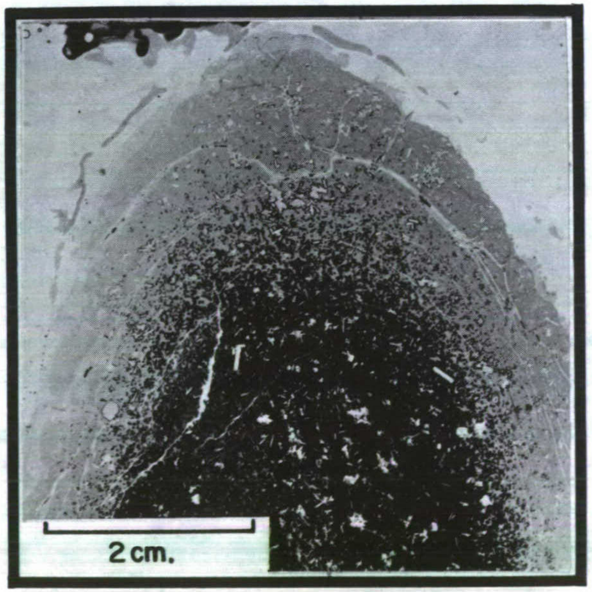

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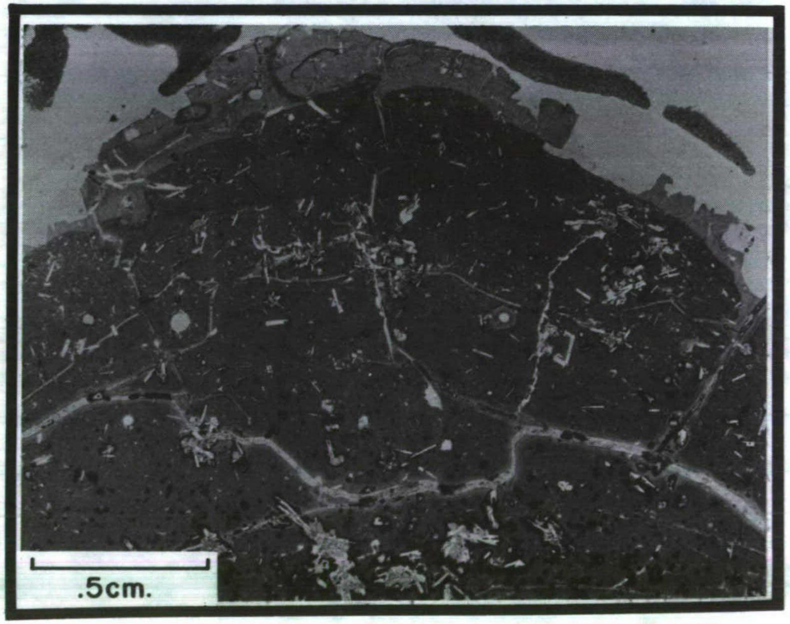
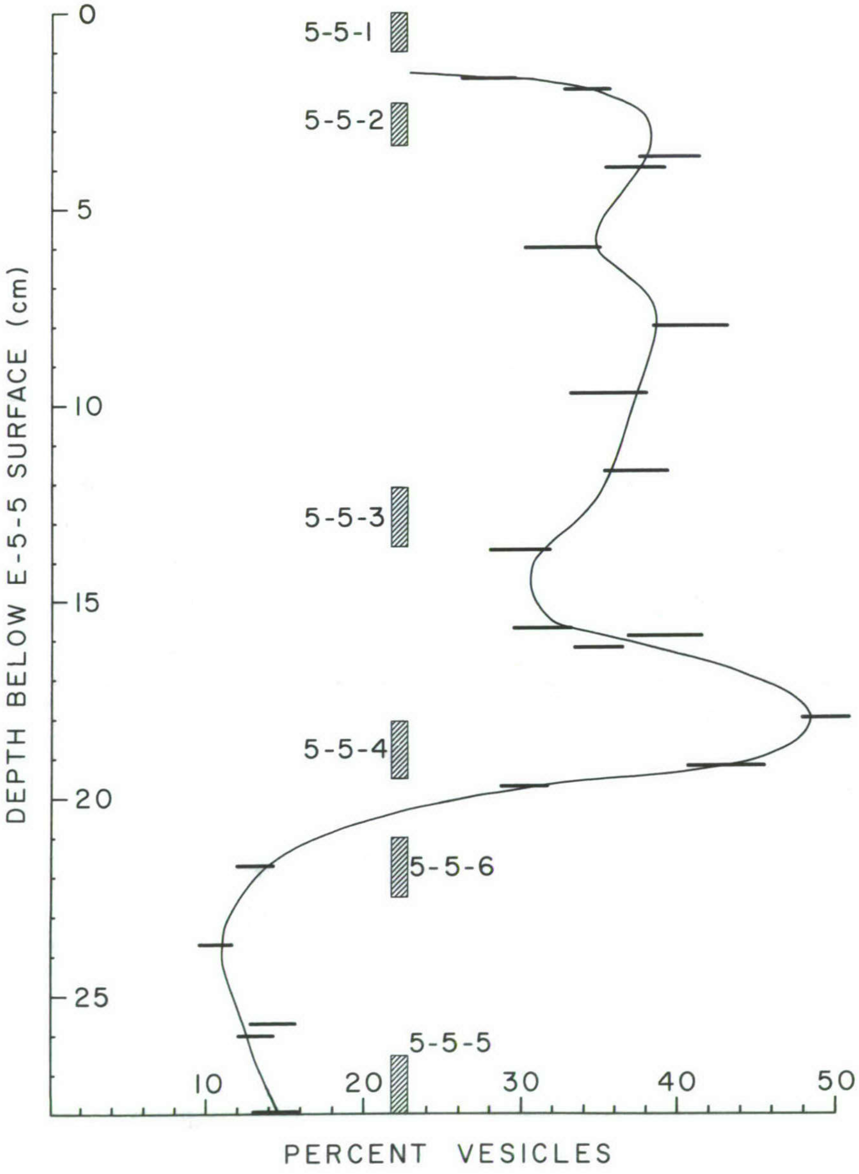
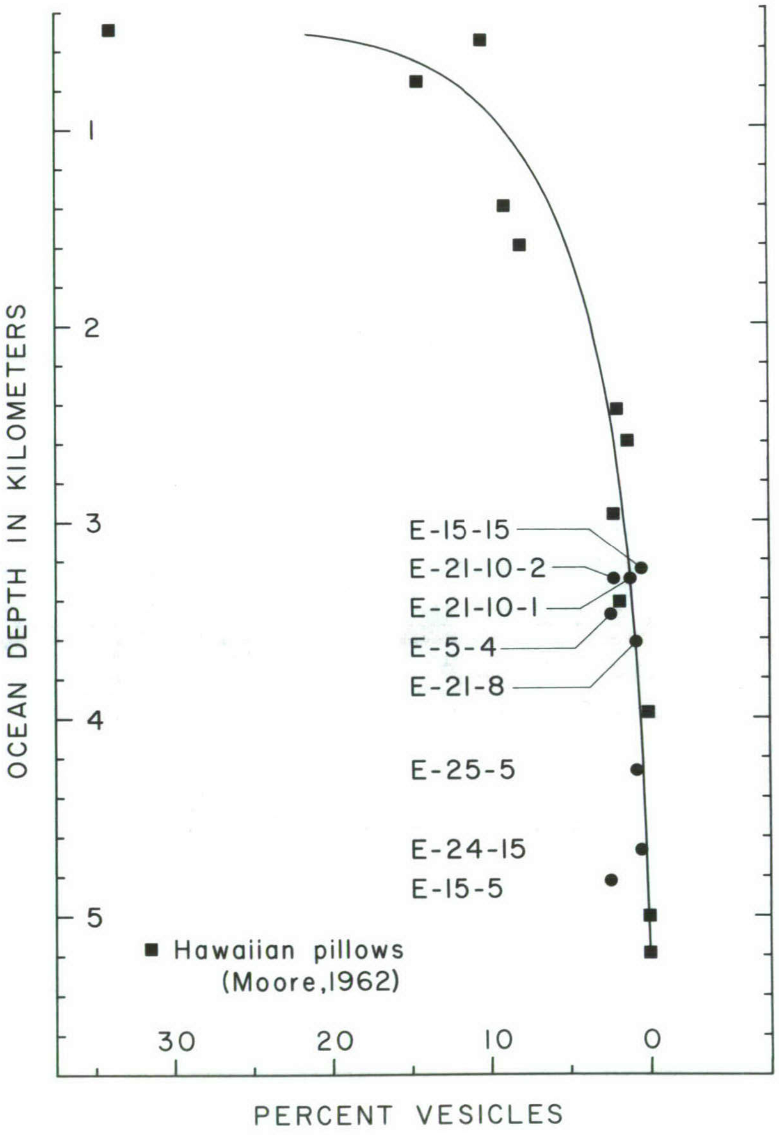


Figure 2.--Vesicularity vs. Depth in E-5-5
Chemically analyzed intervals are represented by diagonal lines with sample numbers

Figure 3.--Pillow Vesicularity vs. Ocean Depth


DEPTH BELOW E-5-5 SURFACE (cm)
0
5
10
15
20
25
5-5-1
5-5-2
5-5-3
5-5-4
5-5-6
5-5-5
10
20
30
40
50
PERCENT VESICLES


OCEAN DEPTH IN KILOMETERS
1
2
3
4
5
E-15-15
E-21-10-2
E-21-10-1
E-5-4
E-21-8
E-25-5
E-24-15
E-15-5
■ Hawaiian pillows
(Moore, 1962)
30
20
10
0
PERCENT VESICLES

The vesicle percentage of the pillows is plotted in Figure 3 along with Moore's (1965) data.

Petrography of the Pillows

Palagonite Zone

The rims of these pillows are divided into four layers discounting any manganese oxide crust which is not considered a part of the rock itself (Fig. 4).

The palagonite and clear glass layers may vary appreciably in thickness depending upon the degree of hydration and preservation of the pillow rind. In general, the palagonite layer varies from 0.5 mm. to 2 mm. in thickness, is reddish to yellowish brown in color, and is in sharp contact with the clear glass below it. The only minerals definitely identified in the palagonite are phillipsite and montmorillonite.

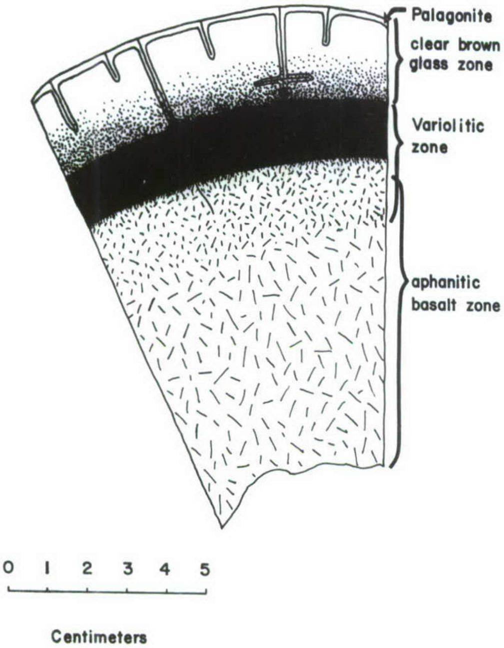
Clear Glass Zone

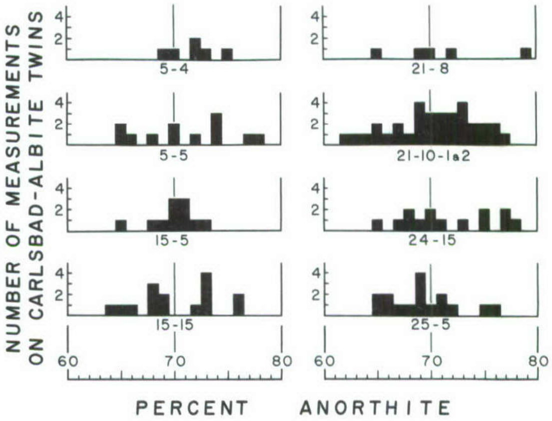
Inward from the palagonite layer, there is a zone of pale yellowish-brown transparent glass normally from 5 to 17 mm. in thickness and commonly containing phenocrysts of olivine and plagioclase. The inner portion of this clear glass is speckled due to minute dark brown to black cryptocrystalline spherules (Plate 2a). Under high magnification these spherules are observed to be composed of fibrous or feathery, felted microlites dusted with very minute incipient

Figure 4.--Diagram of Pillow Zones

Figure 5.--Phenocryst Plagioclase Compositions in Pillows

Figure 6.--Alkalis vs. Silica Diagram
Solid circles are pillow glass and variolitic zones; open circles are aphanitic interiors of pillows. Lines connect two analyses from same pillow. Squares are olivine enriched pillows from the flanks of Hawaii (Moore, 1965).


Palagonite
clear brown glass zone
Variolitic zone
aphanitic basalt zone
0 1 2 3 4 5
Centimeters


NUMBER OF MEASUREMENTS ON CARLSBAD-ALBITE TWINS
4
2
5-4
21-8
5-5
21-10-1a2
15-5
24-15
15-15
25-5
60
70
80
PERCENT ANORTHITE

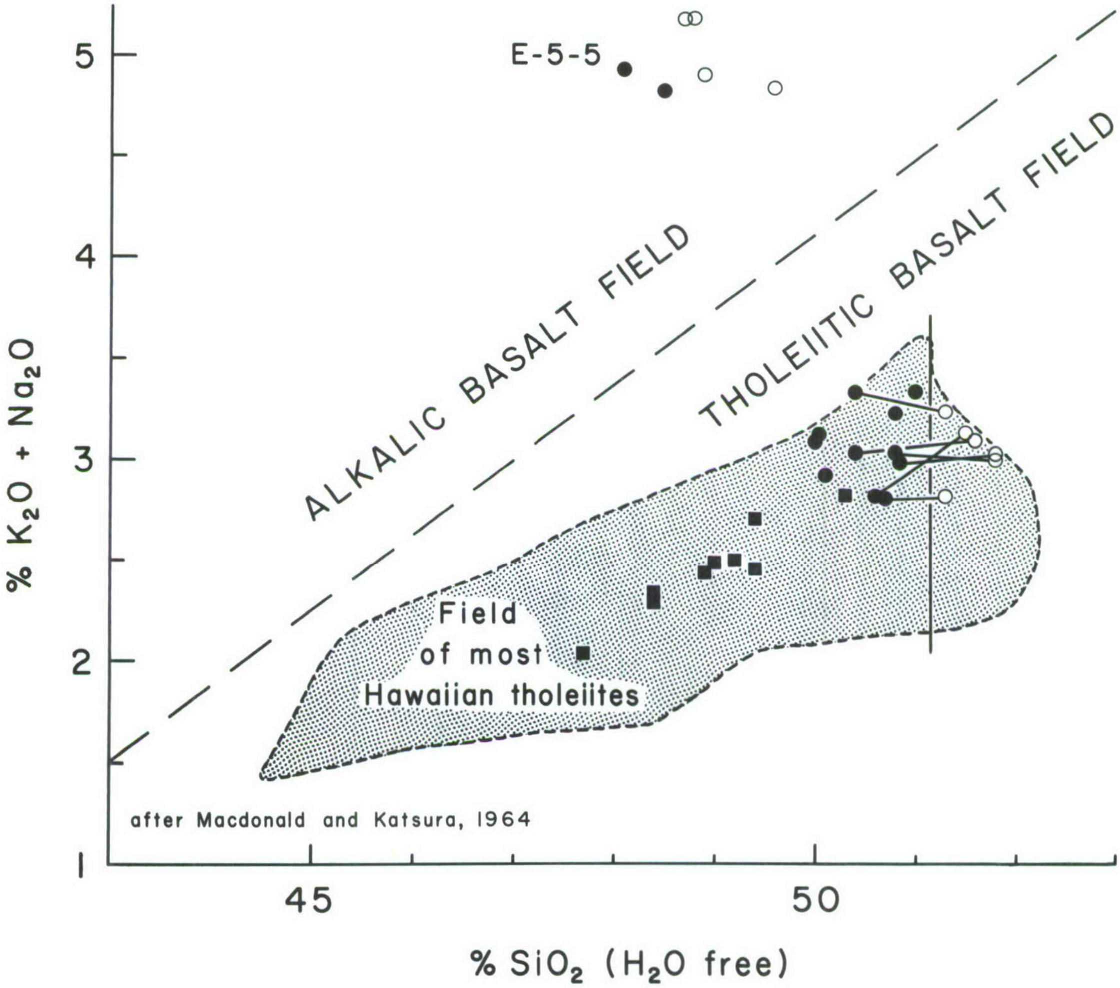

E-5-5
ALKALIC BASALT FIELD
THOLEIITIC BASALT FIELD
Field of most Hawaiian tholeiites
after Macdonald and Katsura, 1964
% K₂O + Na₂O
1
2
3
4
5
45
50
% SiO₂ (H₂O free)

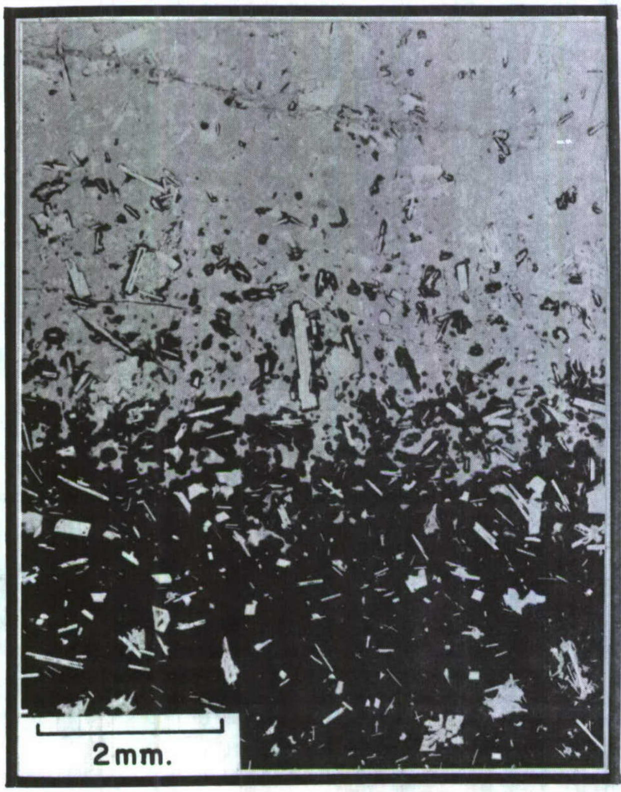
Plate 2.

a. Clear Glass to Variolitic Transition showing nucleation of varioles around phenocrysts of olivine and plagioclase (E-21-10-2).

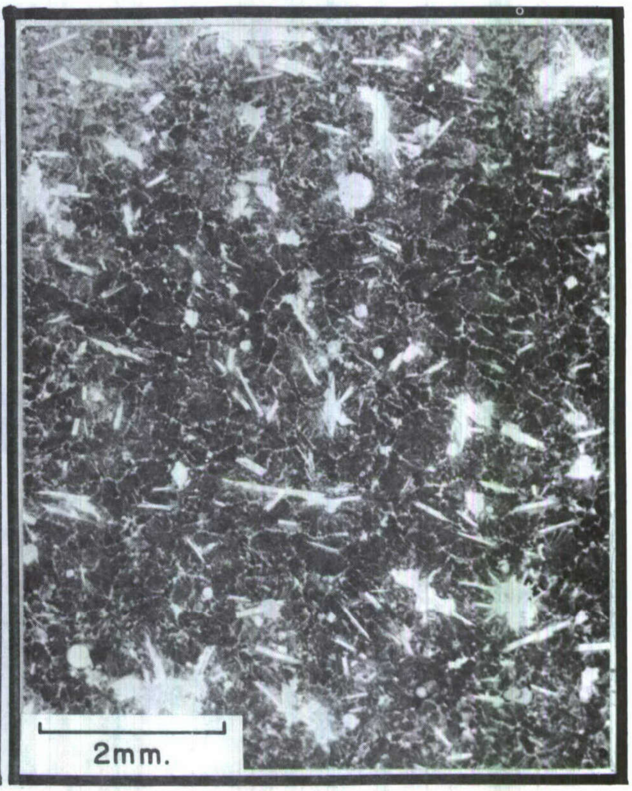
b. Variolitic Texture at its fullest development in dark red-brown variolitic zone of E-15-15.

c. Variolitic Zone with Dusty Opaques. The fine, fibrous pyroxene and incipient opaques give a fuzzy appearance to the groundmass and edges of the phenocrysts (E-21-10-2).

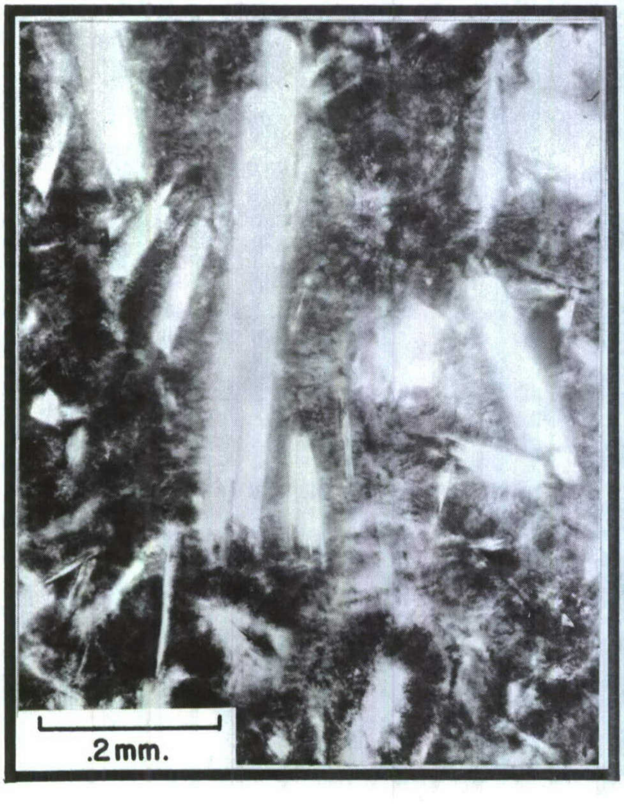
d. Variolitic Zone with Fine Opaques. The groundmass pyroxene has formed fan-shaped and plumose aggregates with opaques in the intervariolitic spaces (E-21-10-2).



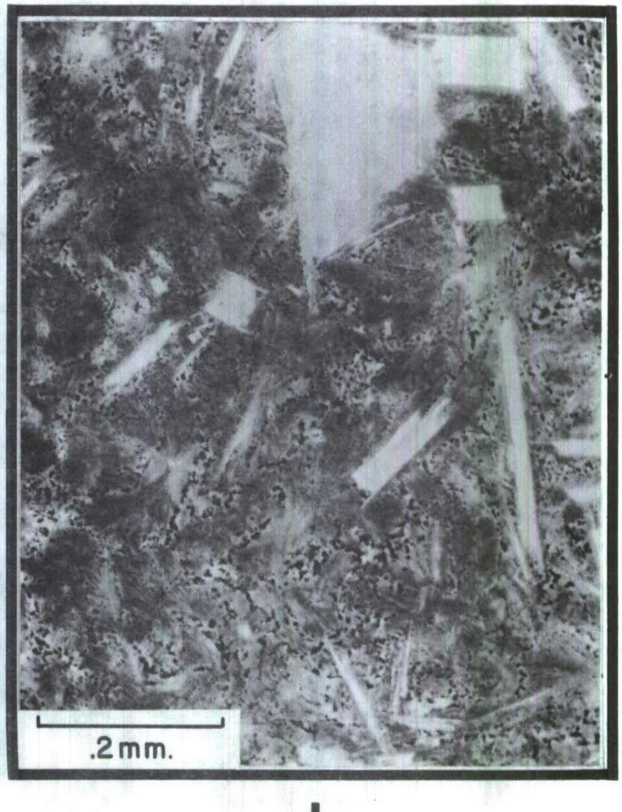
a



b



c



d

opaque minerals. The spherules commonly nucleate about phenocrysts of plagioclase and olivine.

Variolitic Zone

Below the transparent glass the spherules increase in density and size until they form a nearly opaque, dark brown or dark reddish brown "variolitic" zone (Plate 2b). "Variolitic" is used here to mean a texture comprised of subparallel fibers of clinopyroxene arranged in spherical or polygonal units. This dark variolitic zone varies from 5 to 12 mm. in thickness and, where pillows are thick enough, grades inward to a lighter brown variolitic zone (Plate 3a) and then to a very fine-grained basalt toward the center of the pillows (Plate 3b). The pahoehoe toes do not exhibit the fine-grained stage of crystallization in their interiors.

The exceedingly fine size of the microlites comprising the varioles generally prohibits measurement of their optical properties. Where previous mineralogic identification of the varioles has been attempted they have been considered to be incipient crystals of feldspar, or intergrowths of feldspar and clinopyroxene. By tracing the progressive growth of the varioles into the essentially holocrystalline, fine-grained interior of the pillows where optical measurements are possible, the varioles can be observed to be incipient clinopyroxene crystals possibly contaminated with

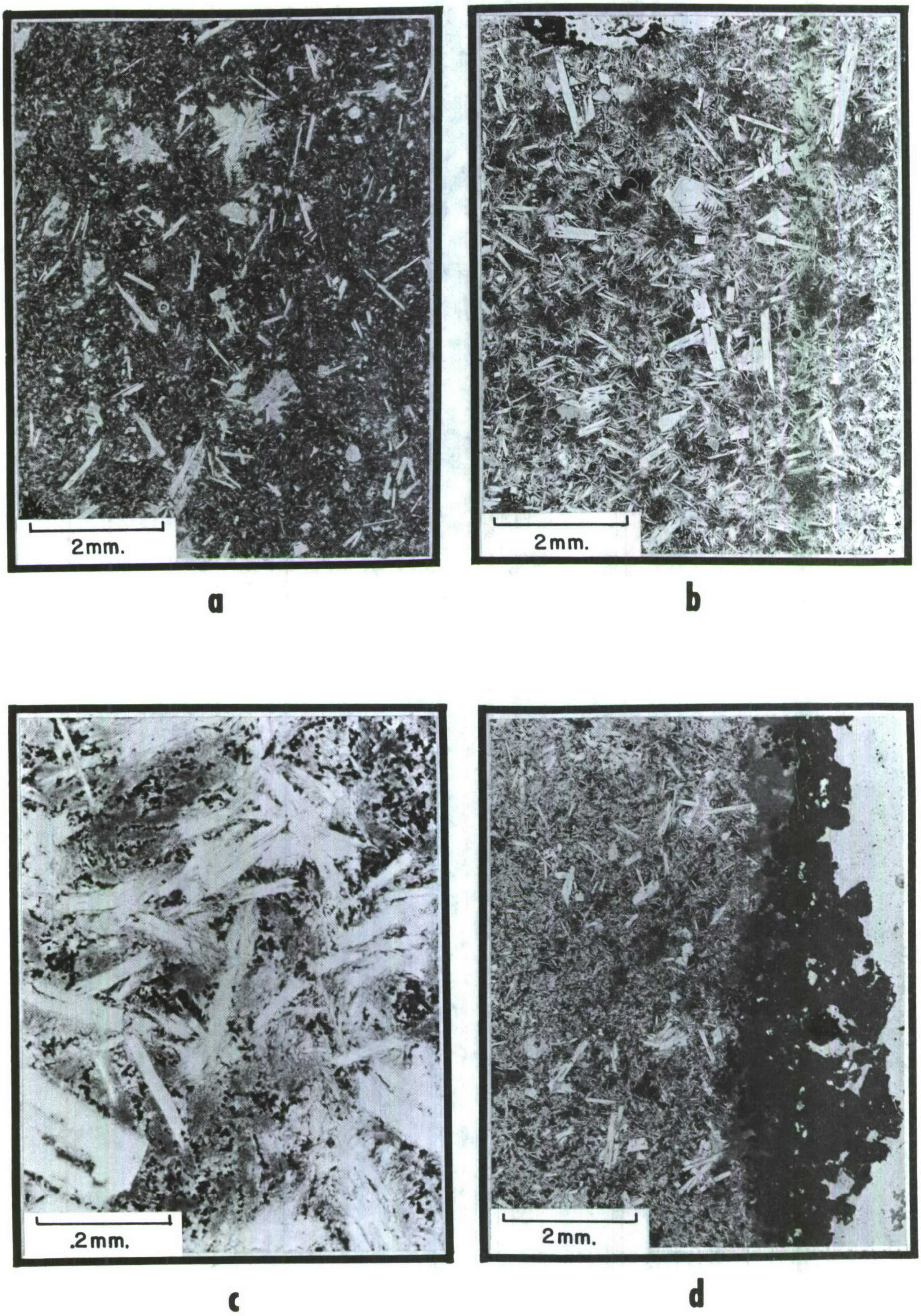
Plate 3.

a. <u>Variolitic to Aphanitic Transition</u>. Varioles were breaking up into smaller, discrete, equigranular clinopyroxene crystals when crystallization was arrested (E-15-15).

b. <u>Aphanitic Texture</u>. Groundmass is composed of plagioclase microlites and small, discrete clinopyroxene crystals, but turbid patches of variolitic groundmass remain. A large skeletal olivine phenocryst is near center of photograph (E-21-10-2).

c. <u>Aphanitic Zone with Larger Opaques</u>. Groundmass granules of pyroxene have lost fibrous appearance (Plate 2d) and are more equigranular (E-21-10-2).

d. <u>Hydrated Aphanitic Zone with Sorbed Iron and Manganese Hydroxides</u> near joint surface. Turbid appearance of rock near hydroxide surface suggests hydrated glass in this zone.


2mm.
a
2mm.
b
.2mm.
c
2mm.
d

plagioclase. The change in color from dark brown or dark reddish-brown to light brown from clear glass to crystalline interior respectively, is accompanied by the development of titano-magnetite microlites. The opaques exhibit a sequence of development from dispersed dust to discrete skeletal crystals which increase in size, decrease in number and segregate at the peripheries of the varioles (Plates 2c, d, and 3c).

In some sections a subparallel arrangement of the clinopyroxene fibers in each of the varioles can be discerned. Individual varioles of the variolitic zone are polygonal at their largest development due to mutual growth interference (Plate 2b). Within a relatively short interval the varioles reorganize into fans and plumes of coarser fibers which bear a strong resemblance to quench clinopyroxene, as illustrated by Yoder and Tilley (1962, p. 530). Within a longer (∿1.0 cm.) interval these fans and plumes give way to discrete, smaller equant grains of clinopyroxene in the light-brown, fine-grained basalt. It is only in or below the variolitic-aphanitic basalt transition that minute laths of truly matrix plagioclase can be seen to appear where they are laminated with the clinopyroxene fibers. Measurement of these feldspars by the Michel-Lévy method indicates a range in composition from An_{52} to An_{56}. The fine, optically interfering microlites comprising the varioles are undoubtedly intimately mixed with glass although no glass can be distinguished. The presence of water in excess of 2.0% in the variolitic zones of E-24-15 and E-25-5 may be interpreted as indirect evidence of glass in this zone. Hydration of the aphanitic zone of E-15-15 adjacent to a joint (Plate 3c) also indicates the presence of glass in this zone.

General Petrography

One of the most conspicuous features of the clear glass rim is the subparallel alignment of feldspar laths roughly parallel to the pillow zones. This alignment is less evident below the variolitic zone. All zones in the Eltanin pillows contain agglomerates of relatively large feldspar and olivine, or feldspar and pigeonite or augite phenocrysts. Zoning of the domal-shaped, euhedral to skeletal olivines is not discernible; whereas four of the pillows contain large, zoned plagioclases, only E-21-10-2 contains plagioclase which appears to have been resorbed. Measurements of combined albite-Carlsbad twins of only the unzoned plagioclase phenocrysts in the pillows reveal a rather calcic range in composition between An_{62} and An_{80}. The concentration range common to all of the pillows lies between An_{65} and An_{75} (Fig. 5). This range is only slightly more sodic than the range of An_{70} to An_{76} for phenocrysts of basalts from the Mid-Atlantic Ridge reported by Quon and Ehlers (1963).

The purplish color and strong inclined dispersion of the pyroxene in E-5-5 indicate that it is high in titanium. Pigeonite was identified in all of the tholeiites by its small positive optic angle.

Alteration of the Pillows

Three types of alteration were found in the pillows: hydration, and two types of deuteric alteration. Moore (1965) sufficiently described hydration so the following discussion will deal with the deuteric types.

Chloritization

The first type of alteration is generally associated with the inner, aphanitic zone of the pillows and is characterized by the following minerals: reddish-brown chlorite (clinochlore?) and hematite in vesicles, (E-5-5); chlorite and ferric iron staining after olivine, (E-15-15); talc in vesicles and after olivine, (E-21-8); magnesite after olivine, (E-21-10-2); chlorite (?), (E-25-5). E-5-5 and E-25-5 have a higher concentration of alteration products (>7.0% by volume) in their interiors than do the other pillows whose alteration products do not exceed 2.0% by volume.

In some instances pseudomorphs of chlorite after olivine are found in all stages from perfect olivine outlines to nearly circular fillings which might otherwise be called vesicles. The crystalline size of the alteration minerals is generally too fine-grained to specifically identify them or to determine their relative percentages precisely. These particular alteration products were not found in the glass layer of the pillows, however, and are less prominent or are absent in the variolitic zone.

Serpentinization

The second type of alteration occurs invariably next to fractures and joints and in some cases is found in the variolitic zone. It involves the replacement of olivine by a material having the optical properties of α-serpentine (Deer, Howie, and Zussman, 1962, p. 182). In hand specimen the altered zone adjacent to joints is darker in color and is a surprisingly constant 6 mm. in thickness among all the pillow fragments (Plates 4a and 4b).

The fibrous serpentine is bright green farthest from fractures but becomes progressively more contaminated with ferric oxide and hydroxide stains toward fractures and joints. In all of the pillows but E-5-4, which contains no olivine, serpentine is found in vesicles, joints and fractures as well as replacing olivine. In E-15-15 serpentine is found in the intervariole region at the base of the variolitic zone. Iron stains are prominent near joints and fractures where goethite, hematite and serpentine are found as fracture fillings up to 0.3 mm. thick (Plates 4c, d). Secondary magnetite is found within bright yellowish-green serpentine near joints of E-21-10-2 although the serpentine adjacent to the joints is stained reddish-brown and no secondary magnetite occurs.

In E-24-15 the minute opaque crystals, normally found in the intervariole region, are absent adjacent to fractures throughout the variolitic zone where, in addition, the color is an anomalously light tan. Within the variolitic zone, away from the fractures, the color is dark brown and it again contains intervariolitic opaques. Olivine in the clear glass zone is completely free from both types of deuteric alteration.

Chemistry of the Pillows

The results of the chemical analyses are given in Table 2 with their C.I.P.W. norms calculated water free in percent by weight. In Appendix A are listed the differences between the duplicate analyses.

All of the summed percentages with the exceptions of E-5-4-1 and E-25-5-3 are low which suggests a systematic error. This is probably due in part to the recommended

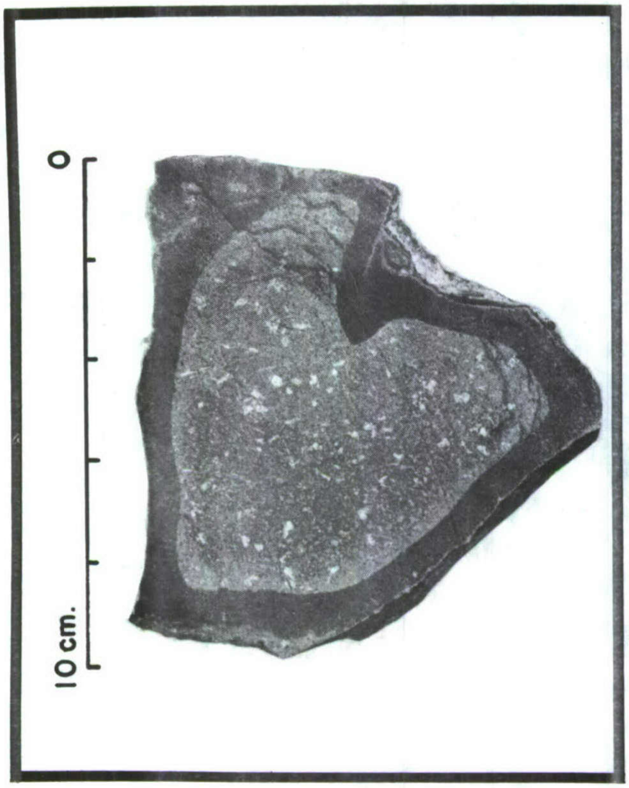
Plate 4.

a. Section Normal to Columnar Jointing in fragment E-21-10-2 showing 6mm. thick serpentinized rim of pillow fragment.

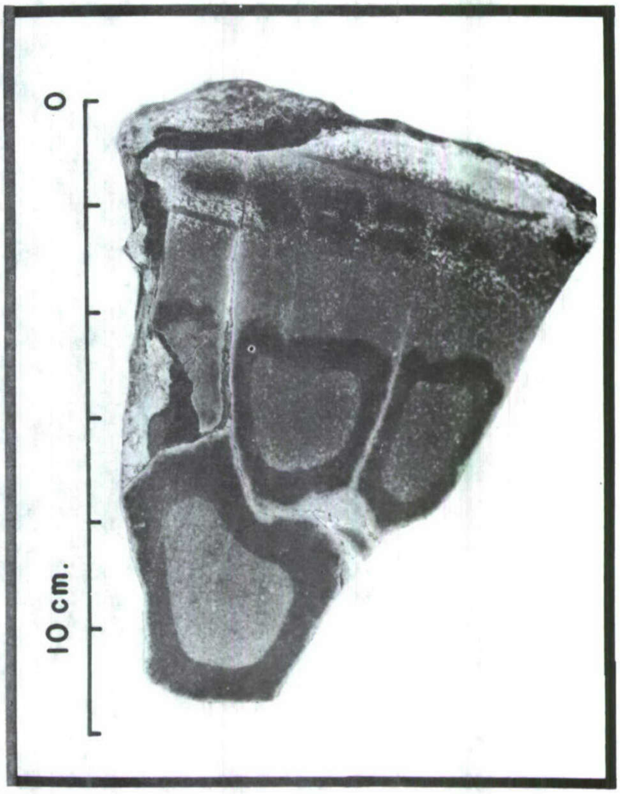
b. Section Normal to Pillow Surface of E-21-8 showing darker serpentinized zones adjacent to fractures and lighter goethite stains in fractures. Black ferromanganese crust is on upper left corner of fragment. Note typical wedge-shaped outline of pillow fragment.

c. Serpentine and Iron Stains in Vesicles. Serpentine (grey areas) line vesicle walls and darker central areas are reddish-brown stained serpentine (E-21-10-2).

d. Serpentine and Hematite in Fracture of E-21-10-2.



a



b

c

d

TABLE 2

CHEMICAL ANALYSES AND C.I.P.W. NORMS OF ELTANIN PILLOW ZONES

	W-1	5-4-1a	5-4-1	5-4-2	5-5-1	5-5-2	5-5-3
		G	G	V	G	V	B
Chemical data (wt. %)							
SiO_2	52.5	48.2	49.5	48.7	47.2	47.1	48.9
Al_2O_3	14.9	13.8	13.8	14.6	14.4	14.5	15.5
Fe_2O_3	.68	12.72	1.82	2.17	2.86	6.03	4.35
FeO	9.30		9.73	9.22	8.46	6.11	5.85
MgO	6.52	5.79	6.68	5.91	6.92	5.61	5.17
CaO	10.92	9.22	10.83	11.14	9.55	9.60	10.35
Na_2O	2.15	2.69	2.67	2.68	3.47	3.11	3.40
K_2O	.61	.80	.40	.32	1.38	1.58	1.38
H_2O+	.65	----	1.55	1.33	1.53	1.18	.80
H_2O-	.07	----	.86	.39	.30	.58	.11
TiO_2	1.10	2.12	2.06	2.04	2.71	2.46	2.71
P_2O_5	.14	.17	.18	.24	.52	.53	.57
MnO	.17	.14	.14	.15	.36	.15	.12
Total	99.71	95.65	100.22	98.89	99.66	98.54	99.21
total Fe as Fe_2O_3	11.00	12.72	12.62	12.40	12.25	12.81	10.84
C.I.P.W. norms (wt. %)							
Qz				.10			
Or			2.40	1.94	7.48	9.54	8.21
Ab			22.98	23.31	26.95	26.91	28.98
An			24.91	27.62	18.03	21.42	23.13
Di			23.42		18.14	18.79	19.75
Hy			18.51	27.69	4.59		5.76
Wo				11.51			
En						6.62	
Ol			.65		15.10	1.63	1.20
Mt			2.71	3.26	3.84	9.02	6.41
Il			3.99	3.99	4.74	4.79	5.20
Ap			.43	.58	1.13	1.28	1.36
Norm. Plag. composition mol. % An			50	52			

G - glass zone of pillow
V - variolitic zone
B - aphanitic basalt zone

C - corundum
Rt - rutile

TABLE 2--Continued

5-5-4 B	5-5-6 B	5-5-5 B	15-5-1 V	15-5-2 B	15-15-1 V
48.0	47.4	47.5	49.8	51.4	50.2
15.4	15.0	14.8	14.8	15.4	14.8
3.71	3.13	2.47	1.54	1.68	1.74
6.77	7.48	8.13	7.90	6.22	7.86
5.57	5.25	5.65	7.50	7.15	7.45
10.26	10.10	9.91	11.39	12.43	11.84
3.43	3.47	3.48	2.75	2.86	2.82
1.40	1.58	1.58	.23	.13	.13
1.28	1.64	1.40	1.15	.38	.44
.09	.10	.09	.45	.06	.14
2.62	2.73	2.76	1.43	1.42	1.42
.56	.56	.57	.14	.14	.14
.12	.13	.13	.15	.12	.13
99.21	98.57	98.47	99.23	99.39	99.11
11.22	11.43	11.49	10.31	8.58	10.46
				.60	
8.02	8.98	8.84	1.36	.77	.76
28.15	28.25	27.89	23.30	24.44	23.72
21.82	19.90	19.04	27.40	29.08	27.19
19.29	20.09	19.54	23.00		24.64
3.97	1.94	2.76	16.37	26.11	15.16
				13.46	
7.35	10.15	12.24	3.25		2.98
5.27	4.41	3.42	2.26	2.48	2.53
4.84	5.00	4.99	2.73	2.73	2.69
1.29	1.28	1.28	.33	.33	.33
			52	53	51

TABLE 2--Continued

	15-15-2	21-8-1	21-8-2	21-8-3	21-10-1-1
	B	G	V	B	V
Chemical data (wt. %)					
SiO_2	51.6	49.5	49.6	51.1	49.9
Al_2O_3	15.5	13.7	13.8	14.3	15.0
Fe_2O_3	1.79	1.39	1.60	2.53	1.66
FeO	6.00	10.47	10.22	7.25	7.99
MgO	7.15	7.30	6.55	6.47	7.49
CaO	12.45	10.19	10.77	11.57	11.65
Na_2O	2.89	2.79	2.52	2.84	2.89
K_2O	.13	.37	.26	.27	.12
H_2O+	.40	----	1.19	.48	.47
H_2O-	.02	.40	.34	.13	.11
TiO_2	1.42	2.10	2.09	2.14	1.61
P_2O_5	.14	.18	.18	.19	.16
MnO	.13	.18	.14	.15	.14
Total	99.62	98.57	99.26	99.42	99.19
total Fe As Fe_2O_3	8.45	13.01	12.94	10.58	10.53
C.I.P.W. norms (wt. %)					
Qz	.78		.81	2.58	
Or	.77	2.16	1.57	1.61	.70
Ab	24.63	23.38	21.79	24.29	24.08
An	29.15	23.53	26.14	25.75	27.18
Di		20.84			23.33
Hy	25.57	19.53	31.41	24.51	14.64
Wo	13.41		11.38	12.94	
En					
Ol		4.17			4.29
Mt	2.64	2.01	2.39	3.74	2.39
Il	2.72	3.96	4.07	4.12	3.02
Ap	.33	.42	.44	.46	.37
Hm					
C					
Rt					
Norm. plag. composition mol. % An	52	48	53	50	51

TABLE 2--Continued

21-10-1-2	21-10-2-1	21-10-2-2	24-15-1	24-15-2	24-15-3
B	V	B	G	V	V
51.2	50.4	50.9	41.6	48.2	49.0
15.9	15.8	16.5	12.1	13.7	13.9
1.63	.94	1.62	16.9	3.00	3.41
6.17	7.93	6.06	.00	9.25	8.66
7.09	7.75	7.00	3.23	5.96	6.26
12.02	11.81	12.42	1.92	9.27	10.89
2.92	2.72	2.72	1.34	2.55	2.54
.17	.10	.11	3.22	.59	.32
.31	.48	.25	9.46	2.88	1.57
.08	.12	.06	4.96	1.75	.53
1.61	1.33	1.34	1.42	2.18	2.10
.16	.13	.13	.11	.16	.19
.11	.12	.12	.59	.18	.16
99.37	99.63	99.23	96.85	99.67	99.53
8.48	9.74	8.35	16.9	13.27	13.02
.42		.46	15.51	2.17	2.19
1.01	.58	.66	22.94	3.66	1.94
24.94	22.54	23.25	13.68	22.66	22.03
30.06	29.99	32.82	10.62	25.42	26.22
	21.63				
25.54	16.65	25.61		27.62	26.32
12.14		11.92		9.10	11.63
			9.67		
	4.48				
2.41	1.35	2.39		4.61	5.11
3.10	2.48	2.58	2.69	4.36	4.10
.38	.30	.31	.31	.40	.46
			20.44		
			3.84		
			.30		
53	55	57	42	51	53

TABLE 2--Continued

	25-5-1a	25-5-1b	25-5-2	25-5-3
	G	G	V	B
Chemical data (wt. %)				
SiO_2	44.9	49.6	49.6	50.9
Al_2O_3	15.2	15.0	14.9	15.6
Fe_2O_3	7.56	1.62	4.06	3.88
FeO	3.81	8.21	6.77	5.21
MgO	4.44	6.92	6.42	6.01
CaO	5.69	10.29	11.20	12.00
Na_2O	2.72	2.79	2.88	3.01
K_2O	1.83	.47	.41	.21
H_2O^+	8.15	1.93	1.10	.67
H_2O^-	2.75	.61	.29	.32
TiO_2	1.88	1.68	1.61	1.70
P_2O_5	.14	.15	.16	.17
MnO	.16	.14	.14	.14
Total	99.23	99.41	99.54	99.82
total Fe as Fe_2O_3	11.79	10.73	11.57	9.66
C.I.P.W. norms (wt. %)				
Qz	4.97		1.10	3.08
Or	12.22	2.84	2.47	1.25
Ab	26.00	24.11	24.79	25.74
An	26.96	27.60	26.98	28.74
Di		19.20		
Hy		18.74	23.21	19.12
Wo	1.63		11.89	12.65
En	12.46			
Ol		1.46		
Mt	8.78	2.42	6.05	5.74
Il	4.05	3.27	3.12	3.27
Ap	.38	.36	.39	.41
Hm	2.55			
Norm. plag. compositon mol. % An	49	52	50	51

values for W-1 whose percentages sum to 99.71%. E-24-15-1 is exceptionally low due to a poor water determination. E-5-5 was found in polished section to contain a trace of sulfide which was not chemically determined. E-21-10-2 was seen in thin section to contain a trace of carbonate which was not chemically determined.

The total alkalis are plotted against the silica percentage for the nine Eltanin pillows in Figure 6. The diagonal dashed line is an empirically determined line which separates the tholeiitic and alkalic fields for Hawaiian basalts (Macdonald and Katsura, 1964). The unhydrated Eltanin samples plot in the upper right portion of the field for most Hawaiian tholeiites except for E-5-5, dredged from the flank of a seamount, which plots in the alkalic basalt field. Submarine tholeiites from the flank of Hawaii containing higher percentages of olivine (Moore, 1965) plot lower in the tholeiitic field.

The same analyses are displayed in the form of a Larsen plot in Figure 7. The percent of each major oxide, adjusted to 100 per cent, is plotted on the ordinate; whereas the abscissa is determined by the formula 1/3 SiO_2 + K_2O - (MgO + FeO + CaO). Larsen proposed this scheme because in rock series oxides other than silica show definite trends and most other variation diagrams in which the oxides are plotted against silica are not particularly informative where small variations in silica are concerned. Total iron is recalculated to FeO and MnO is added to this value in the plot. Each line connects the oxide percent from two portions of the same pillow.

Figure 8 is a Larsen plot of the alkalic basalt E-5-5 and Figure 9 illustrates the mineralogy of the zones from which the samples were taken for chemical analyses.

Figure 10 is an AFM diagram in which the Eltanin tholeiites are compared with the Hawaiian tholeiites. The seven analyses which yielded a total water percentage of greater than 2.0% are shown in Figure 11 which is a Larsen plot similar to that used for the non-hydrated zones.

Magnetic Parameters of the Pillows

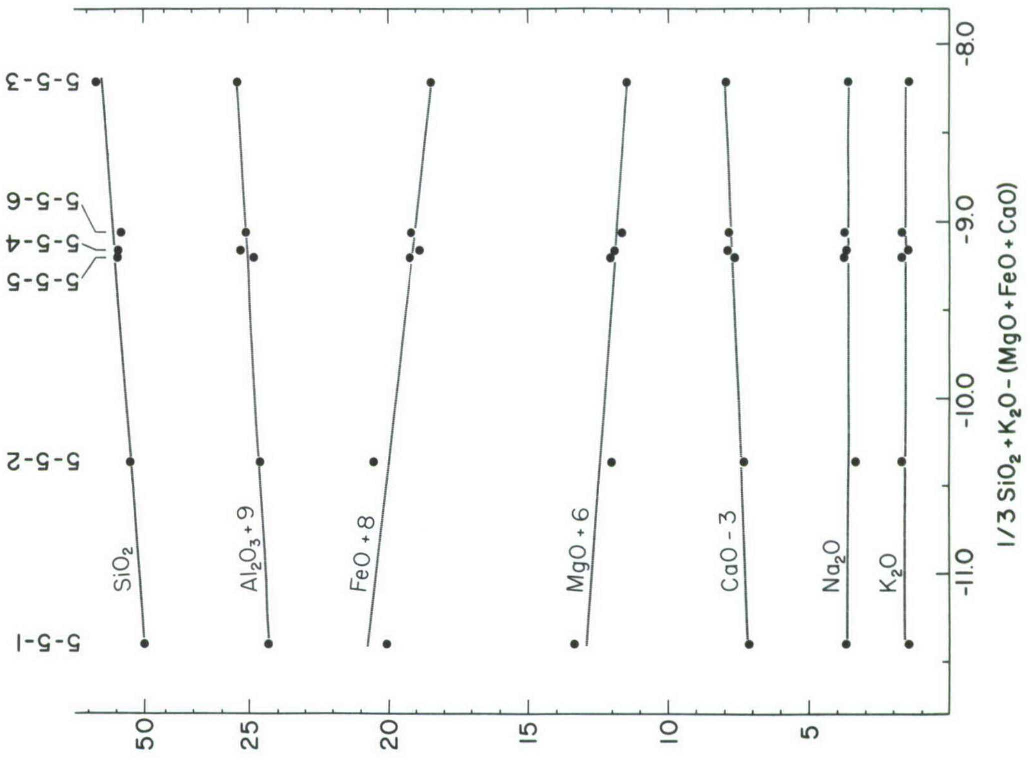
In denoting the magnetic samples each letter at the end of the rock sample number refers to one core and the last number refers to a segment of the core. Unless otherwise noted or displayed the samples are numbered consecutively from glass rim to interior of a basalt fragment.

The natural remnant magnetism (J_0) and magnetic susceptibility (c.g.s. units) of the pillow samples are presented in Figures 12-15 by solid and dashed lines respectively. The alternating field demagnetization curves are displayed in Figures 16-19. The glass rims of the pillows

Figure 7.--<u>Larsen Plot of Unhydrated Tholeiites.</u> <u>Ordinate is per cent oxide.</u> Each heavy line connects two analyses from the same pillow. Vertical line at -11.35 separates the aphanitic pillow zones (on the right) from the glass and variolitic zones (on the left).

Open triangles represent average of 8 Mid-Atlantic Ridge tholeiites (Muir and Tilley, 1966). Solid triangles are other tholeiite analyses (Engel et al., 1965).

Figure 8.--<u>Larsen Plot of E-5-5.</u>


5-5-1
5-5-2
5-5-5
5-5-4
5-5-6
5-5-3
SiO$_2$
Al$_2$O$_3$ + 9
FeO + 8
MgO + 6
CaO - 3
Na$_2$O
K$_2$O
50
25
20
15
10
5
-11.0
-10.0
-9.0
-8.0
1/3 SiO$_2$ + K$_2$O - (MgO + FeO + CaO)

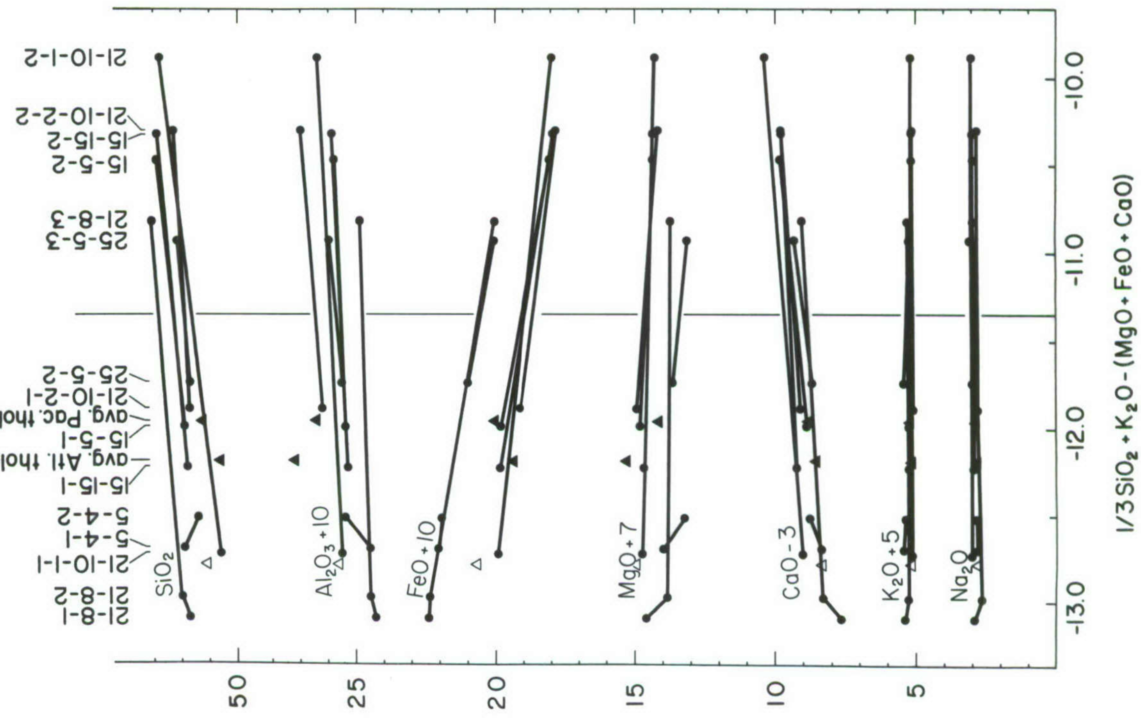
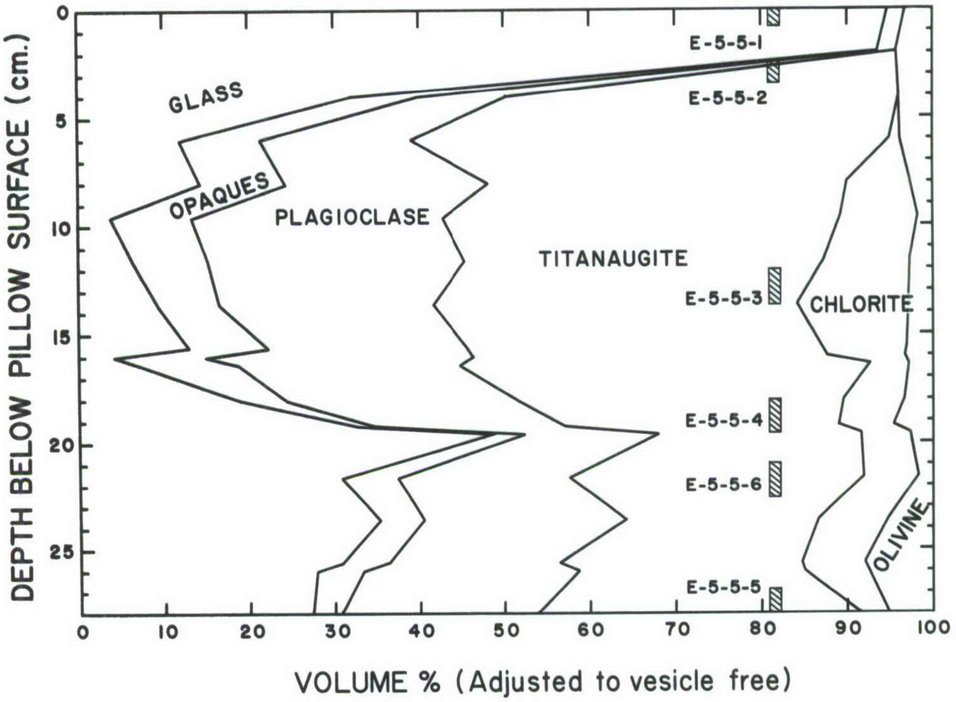

21-8-1
21-8-2
21-10-1-1
5-4-1
5-4-2
15-15-1
avg. Atl. thole.
15-5-1
avg. Pac. thole.
21-10-2-1
25-5-2
25-5-3
21-8-3
15-5-2
15-15-2
21-10-2-2
21-10-1-2
SiO$_2$
Al$_2$O$_3$ + 10
FeO + 10
MgO + 7
CaO - 3
K$_2$O + 5
Na$_2$O
50
25
20
15
10
5
-13.0
-12.0
-11.0
-10.0
1/3 SiO$_2$ + K$_2$O - (MgO + FeO + CaO)

Figure 9.--Modal Analysis of E-5-5. Chemically analyzed intervals are represented by diagonal lines.

Figure 10.--AFM Diagram. Total iron is computed as FeO. Solid circles represent analyses of glass and variolitic zones of pillows; open circles represent aphanitic zones. Each line connects two analyses from the same pillow. Squares represent pillows from the flanks of Hawaii (Moore, 1965).


DEPTH BELOW PILLOW SURFACE (cm.)
0
5
10
15
20
25
GLASS
OPAQUES
PLAGIOCLASE
TITANAUGITE
CHLORITE
OLIVINE
E-5-5-1
E-5-5-2
E-5-5-3
E-5-5-4
E-5-5-6
E-5-5-5
0
10
20
30
40
50
60
70
80
90
100
VOLUME % (Adjusted to vesicle free)

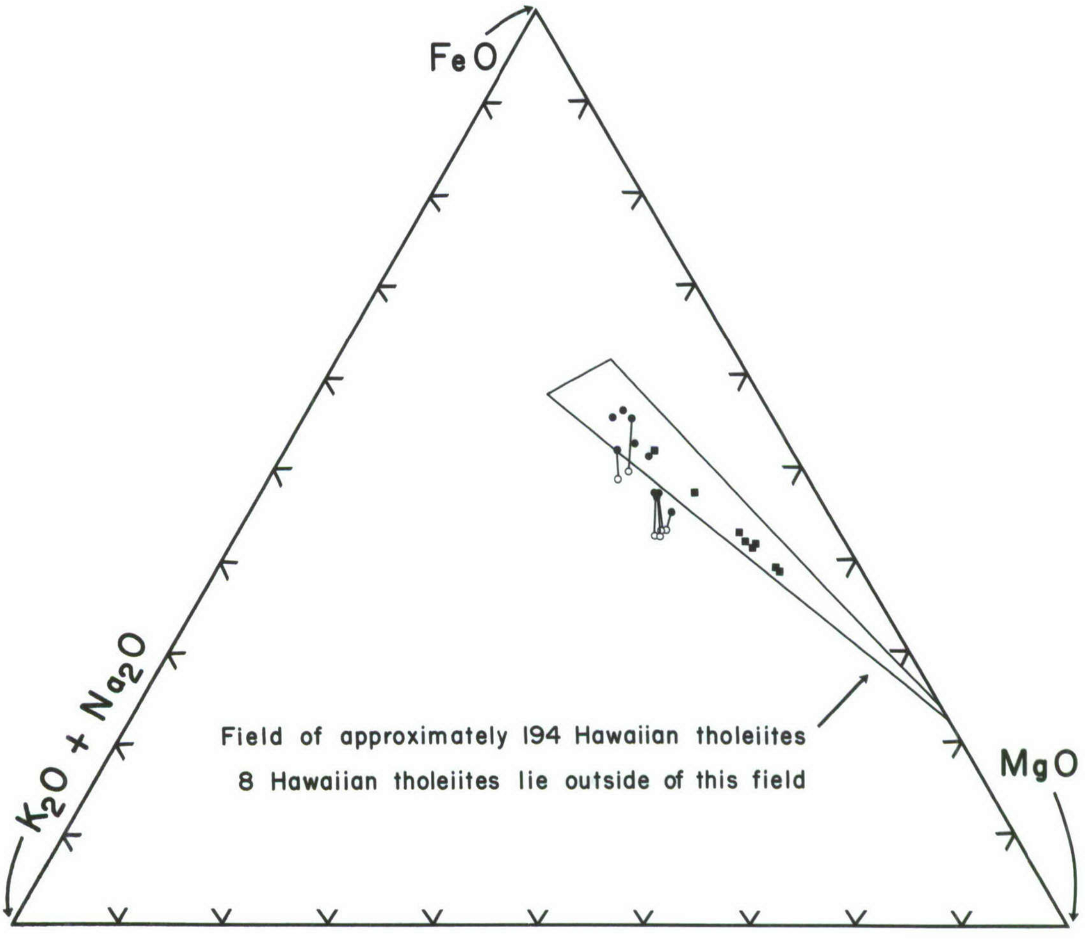
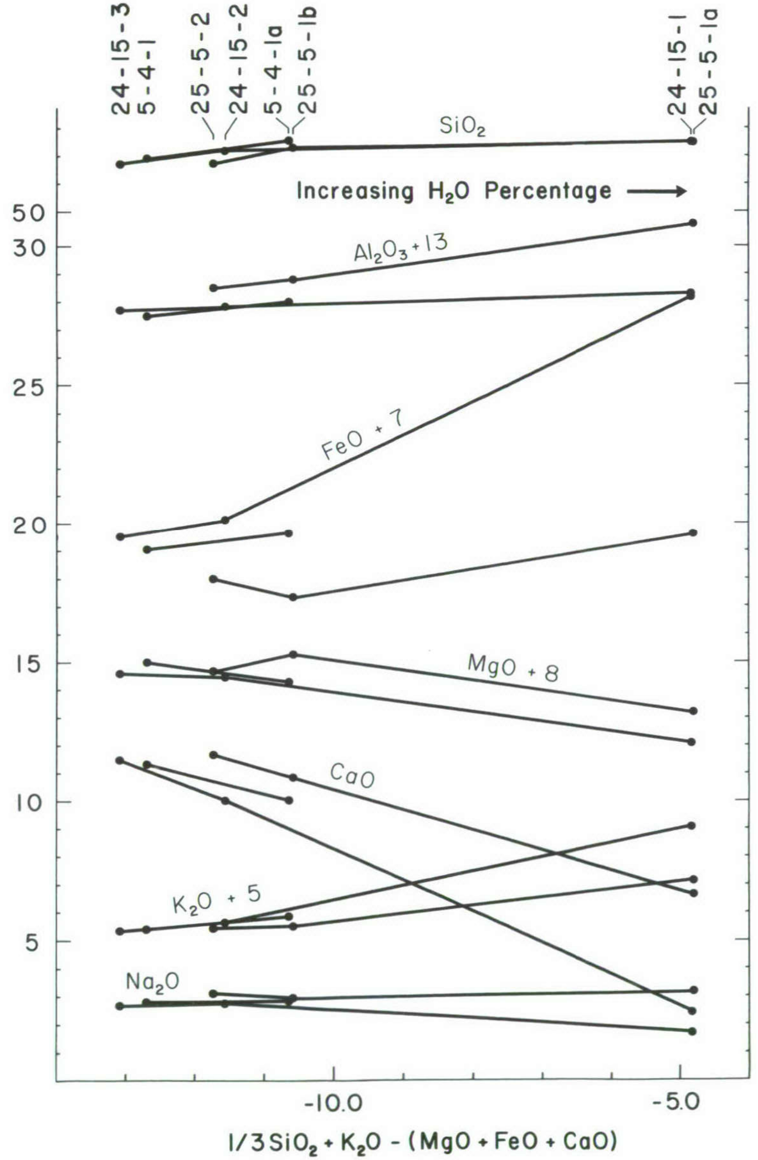
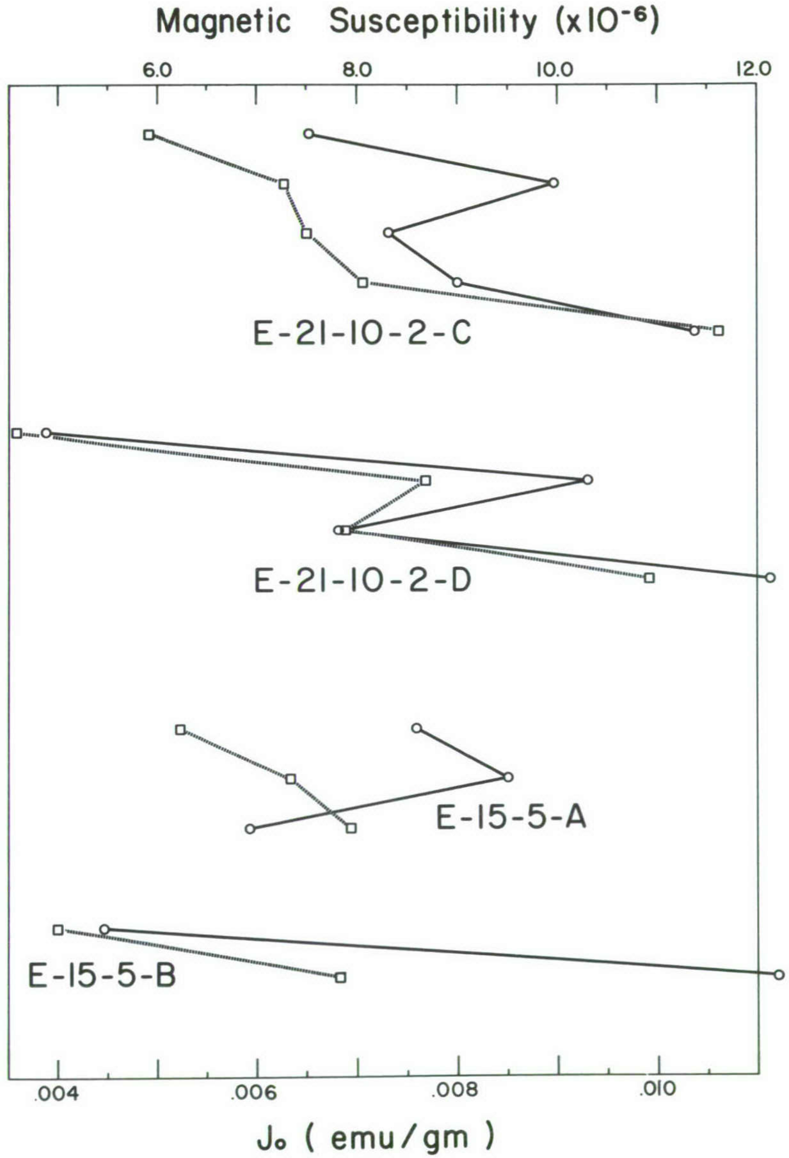

FeO
$K_2O + Na_2O$
MgO
Field of approximately 194 Hawaiian tholeiites
8 Hawaiian tholeiites lie outside of this field

Figure 11.--<u>Larsen Plot of Hydrated Tholeiites.</u> Ordinate is per cent oxide. Each line connects two analyses from the same pillow.

Figure 12.--<u>Magnetic Data vs. Pillow Depths.</u> Magnetic susceptibility in c.g.s. units.



24-15-3
5-4-1
25-5-2
24-15-2
5-4-1a
25-5-1b
24-15-1
25-5-1a
SiO$_2$
Increasing H$_2$O Percentage →
Al$_2$O$_3$ + 13
FeO + 7
MgO + 8
CaO
K$_2$O + 5
Na$_2$O
50
30
25
20
15
10
5
-10.0
-5.0
1/3 SiO$_2$ + K$_2$O - (MgO + FeO + CaO)



Magnetic Susceptibility (x10^{-6})
6.0
8.0
10.0
12.0
E-21-10-2-C
E-21-10-2-D
E-15-5-A
E-15-5-B
.004
.006
.008
.010
J$_o$ (emu/gm)

are up in the Figures and the interiors of the pillows are plotted downward in the Figures. All data are recorded in Appendix B.

DISCUSSION

Submarine Volcanism Products

The concentric fractures found in the pahoehoe toes (Plates 1c and 1d) probably exist because of the greater differential stresses in the chilled glassy crusts of these toes due to their smaller diameters. It is evident from the number and spacing of the fractures as well as from the poor coherency of the glass fragments in the rims of the toes that as hydration and zeolitization proceed along the fractures the fragments are loosened to yield a friable glass rim composed of a large number of angular glass fragments which are preserved only by a thick ferro-manganese crust.

It is conceivable that the disintegration of such a crust of a submarine flow which is composed of a large number of small pillows and toes may provide an appreciable amount of angular glass fragments or a hyaloclastite.

Vesicularity of Pillows

The data shown in Figure 3 indicate that in submarine pillows, the theoretical pressure-versus-vesicularity relationship is supported and the lava was not appreciably oversaturated in volatiles at the time of cooling.

Toe E-5-4 (Plate 1b), which contains a central cavity, displays the normal sequence of crystallization from its rim to within about 20 mm. from the cavity where the most advanced stage of crystallization is the light-brown variolitic stage. At a distance of 10 mm. from the cavity the light-brown variolitic stage reverts to the red-brown variolitic stage characteristic of the earlier stage of crystallization which is normally found near the rim of the toe. This is interpreted as evidence of contamination by water which somehow entered the hot toe and subsequently expanded to form a central cavity and anomalous vesicles adjacent to the cavity. In view of the evidence for low viscosities in submarine lavas relative to subaerial flows discussed earlier it appears that some cavities previously reported beneath glassy crusts of pillows from depth may be explained by either partial drainage of their molten interior as Macdonald has suggested, or by contamination with sea water, or most likely, by a combination of the two processes.

Alterations

Deuteric alteration of the Eltanin pillows is divided into two types which appear to be related to the amount of water and volatiles involved in the reactions. These types are superimposed in some cases.

Chloritization

The first type of alteration occurs under conditions of minimum water but maximum volatile concentration. The water involved would be dissolved in the lava upon extrusion and is estimated to be about 2.0 per cent or less for reasons to be discussed later. This type of alteration which is found in the interior of the pillow fragments is most likely high temperature in nature and principally involves the formation of chlorite.

Serpentinization

Because serpentine has a higher water content than any of the products of the first type of alteration, and because serpentization is restricted to portions of the rock which were accessible to sea water, it is postulated that the serpentinization is due to reaction with sea water during cooling following jointing and is not due to a reaction between melt water and olivine.

In summary, the petrographic study of alteration in these pillows indicates that deuteric alteration destroys olivine and, in one instance, intervariolitic opaques, produces chlorite and serpentine, and mobilizes iron and serpentine constituents to joints, vesicles and fractures where the iron is oxidized to hematite and goethite.

Reports of deuteric alteration related to jointing in basalts are rare. Smedes and Lang (1955) reported alteration of a late Tertiary columnar basalt flow in which thin zones adjacent to joints contain chlorophaeite, a hydrous mineraloid produced by deuteric alteration of olivine and "glassy base." Fuller (1938) described a late Tertiary volcanic sequence of southeastern Oregon as being deuterically altered in the interiors of jointed columns, although the basalt adjacent to joints is unaltered. Neither of these investigators has considered the widths of the joints and their accessibility to possible water percolation during cooling. It is possible that Smedes and Lang were dealing with an alteration due to water in joints whereas Fuller's volcanic joints were dry as he implied.

Forsterite with 10 mol. per cent Fe_2SiO_4 is serpentinized at 340°C. (water vapor pressure = 1000 atmospheres) whereas pure forsterite is stable in the presence of water vapor above this temperature (Bowen and Tuttle, 1949). This indicates that serpentinization occurs during later stages of cooling, long after the joints have formed. Indeed, the joints must have formed after the major silicate phases have crystallized for there is no observed crystal size difference which can be associated with the joints.

Chemistry of the Pillows

One of the most interesting features of the Eltanin tholeiites (Fig. 6) is that the silica percentages of the fine-grained interiors are apparently higher than the other pillow zones and plot toward the right margin of the tholeiitic field, being roughly separated from their variolitic equivalents by the vertical line at 51.1% silica.

The Larsen plot of Figure 7 illustrates the similarity in composition of the individual pillows even though they were collected from widely scattered localities of the Southern Ocean. Also plotted are an average of six Pacific tholeiites and an average of seven Atlantic tholeiites (Engel and Engel, 1964). These basalts, especially those from the Pacific, differ very little from the Eltanin tholeiites. The only differences are a slightly lower alumina and slightly higher silica content in the Eltanin basalts.

Of particular importance is the establishment of a small but definite change in chemical composition among the different zones of each pillow. The vertical line at -11.35 on the abscissa in Figure 7 separates analyses of the unhydrated glass and variolitic layers on the left from the aphanitic interiors on the right. In these analyses 2.0% total water appears to be the approximate division value between hydrated and non-hydrated glass.

The chemical trend from glass and variolitic layers to the crystalline cores of the pillows is, essentially, a relative decrease in total iron content and a slight decrease in magnesium with a corresponding increase in the other constituent oxides. The data indicate no consistent change in the alkali percentages.

The alkalic basalt pillow is much coarser textured in its interior and therefore any alteration can be more readily recognized in thin section. No alteration rims exist around the olivine in this rock and no obvious corrosion of the olivine is evident. The zone with maximum chloritization is represented on the Larsen plot (Fig. 8) by analysis E-5-5-3. Analyses of three portions of this pillow (E-5-5-4, 5,6) which are more or less equally spaced beneath E-5-5-3 (Fig. 9) cluster on the diagram at a point between the analyses of the variolitic zone and the zone of highest chloritization. Because the lower portion of the pillow represented by the clustered points contains about 30% glass and a notable deficiency in vesicle content (Fig. 2), the clustered points may represent the composition of a part of the alteration zone and chilled glass that became mixed during flowage of the basalt. In this zone circular patches of variolitic and glassy material are found in what appear to be relic vesicles. Whatever the cause of the similarity in the chemistry of the lower portion of the pillow fragment, it is clear that a deficiency in iron and magnesium content exists in the center of the alkalic basalt fragment similar to the deficiency in the tholeiitic pillows. However, in this case the deficiency can be directly associated with deuteric alteration involving the formation of secondary chlorite.

In order to determine whether the variations in iron are due to enrichment in the glass and variolitic zones or depletion in the pillow interiors, a comparison of the iron, magnesium and alkali composition was made with the tholeiites of Hawaii (Fig. 10). Whereas most of the Pacific tholeiite glass and variolitic zones fall within the Hawaiian tholeiite field or slightly below it, the aphanitic zone in the Eltanin basalts in each case plots much lower than the tholeiite field indicating an absolute drop in total iron percentage relative to most Hawaiian tholeiitic rocks.

Hydration of the Pillows

Six analyses of the glass and variolite zones of E-5-4, E-24-15, and E-25-5 yielded a total water content of greater than 2.0% with the exception of E-5-1a in which the water was not determined. E-5-4-1a is believed to have a high water content because of its low chemical total for all constituents except water and because the layer below it has a total H_2O content of 2.41%. These analyses (plotted in Fig. 11) agree with previously published analyses of hydrated-nonhydrated glass pairs in that, relative to silica and alumina, they show a deficiency in calcium, magnesium, and sodium (?) and an excess of total iron, ferric/ferrous ratio, and potassium. The Eltanin basalts show little change in silica and only a slight increase in alumina (Fig. 11). However, the present study does not include examples of highly hydrated tholeiitic glass.

Because the chemical changes in the hydrated zones are only relative, some question arises as to which constituents are actually gained, or which are actually lost, if any. If the data are recalculated water free it is found that, in general, there is little significant change in silica or alumina, in agreement with the results of Noble (1967). If only a decrease in calcium and magnesium occurred then there should be a proportionate increase in all other constituents, which is not the case. If only an increase in potassium and iron occurred then there should be a proportionate decrease in all of the other constituents, which is not the case either. It seems to be safe to assume that silicon and aluminum are not as mobile as most of the other ions in the chemical reorganization upon hydration. Therefore, decreases in calcium and magnesium are offset by increases in potassium and iron. This results in silica and alumina percentages which are close to the original unhydrated material.

The enrichment of glass in potassium with a leaching of magnesium and calcium may be intimately associated with the growth of phillipsite and montmorillonite in the hydrated glass (Hawkins and Roy, 1963).

Iron enrichment in the glass can best be explained by the process of sorption (Nicholls, 1963). The reddish lamellae in the outer palagonite layer of the pillows are most likely due to variations in iron percentage. In some cases iron hydroxides (and possibly manganese hydroxides) form dendritic growths from glass surfaces inward, presumably along fractures

(Plate 3d). In these cases it appears that the transporting agent to the sorption site is sea water.

Although the data are insufficient to make any definite statements concerning the original water content of the tholeiites, it is worth noting that the value found for saturated basalt at a pressure equivalent to 4000 meters water depth and a temperature of 1100°C. by Hamilton, Burnham, and Osborn (1964) is 1.5% which is very close to the maximum H_2O^+ content of what is taken to be unhydrated glass. The pillow zones below the unhydrated glass zones become more dehydrated toward the pillow interiors most likely because of the expulsion of vapors during crystallization.

Magnetic Parameter Variations

The NRM of the pillows characteristically varies from their glass rims to their interiors such that when plotted, as solid lines in Figures 12 and 13, the curves have a zig-zag trend. There are two possible explanations for this phenomenon, one being a change in magnetic mineral grain size and the other being a systematic change in the oxidation state of the titano-magnetite.

The absence of opaques in the clear glass results in a low intensity of magnetization (J in emu/gm). The increase in J in the variolitic zone and drop in J toward the pillow interiors may be due in part to the growth of opaques to a size of single domains (high J) and then to a size of multiple domains in which oppositely directed, lower temperature magnetic moments reduce J.

The variations in J of the pillows may also be explaine by the mechanism of partial oxidation whereby the variolitic zone contains the A component and the aphanitic zone contains both components, A and reversely magnetized B, resulting in a lower J.

An increase in J toward the pillow interiors may be attributed to an increase in the total percentage of magnetic minerals but this cannot explain its drop near the interior of the pillows.

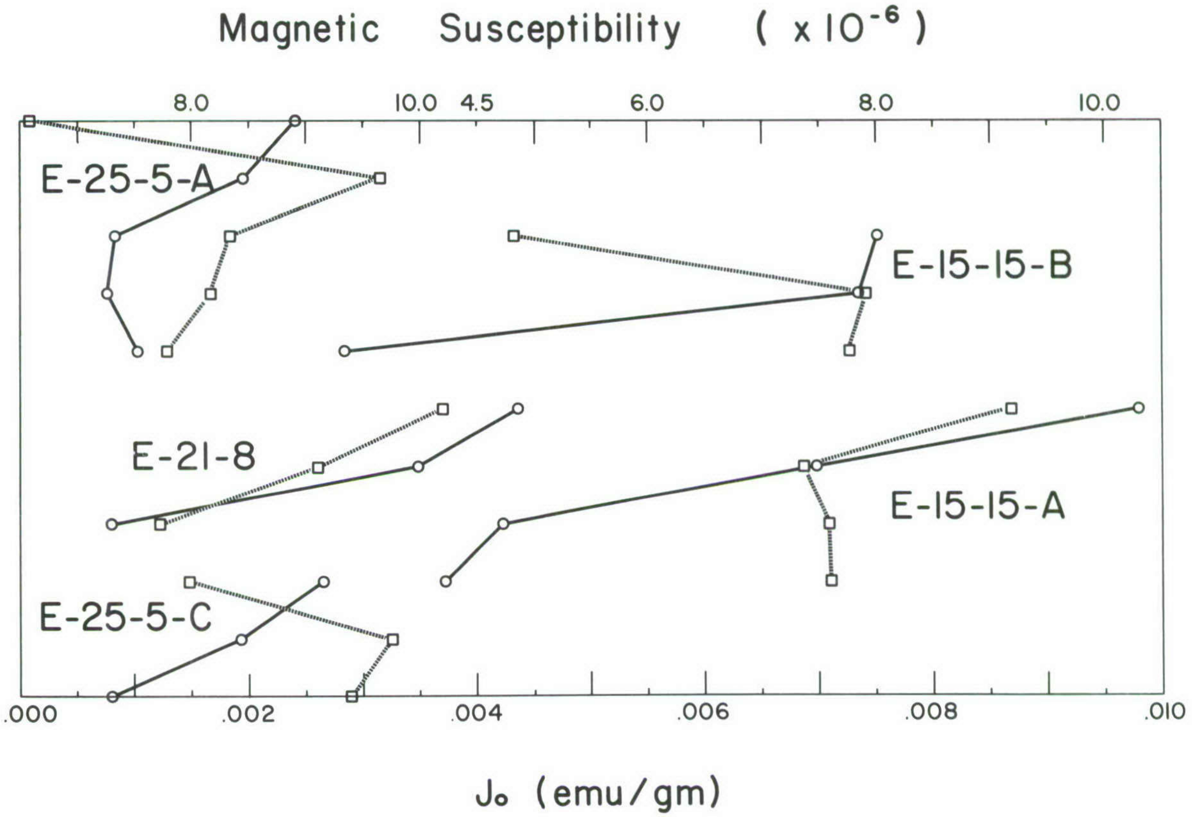
There are common variations in the J curves of Figures 12 and 13 because of the varying thicknesses of the pillow zones, the sample lengths being relatively constant. The absence of an aphanitic basalt zone in the centers of toes E-24-15 and E-5-4 is readily seen in the plot of the remnant magnetism values measured on cores taken through their centers shown in Figure 14. The magnetic intensity does not drop off in their centers (which have not progressed beyond the variolitic stage of crystallization).

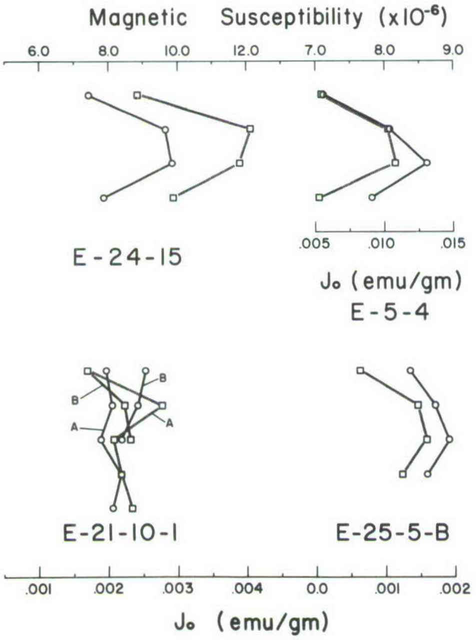
Data for alkalic basalt E-5-5 shown in Figure 15 are not easily explained. The increase in magnetic intensity in the central portion of the rock is well below the zone of maximum deuteric alteration and is not distinguished by any

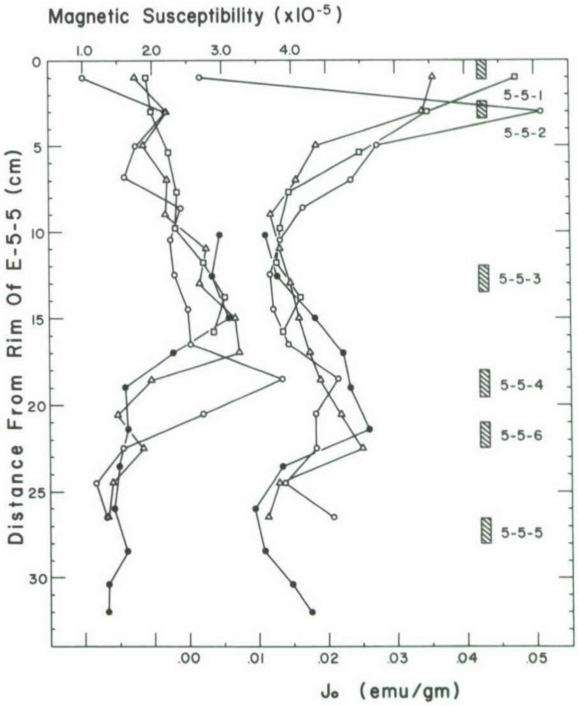
Figure 13.--Magnetic Data vs. Pillow Depths Magnetic susceptibility in c.g.s. units.

Figure 14.--Magnetic Data vs. Pillow Depths Magnetic susceptibility in c.g.s. units.

Figure 15.--Magnetic Data vs. Pillow Depth in E-5-5 Magnetic susceptibility in c.g.s. units.


Magnetic Susceptibility (x10^{-6})
8.0
10.0
4.5
6.0
8.0
10.0
E-25-5-A
E-15-15-B
E-21-8
E-15-15-A
E-25-5-C
.000
.002
.004
.006
.008
.010
Jo (emu/gm)


Magnetic Susceptibility (x10^{-6})
6.0
8.0
10.0
12.0
7.0
8.0
9.0
E-24-15
.005
.010
.015
Jo (emu/gm)
E-5-4
B
B
A
A
E-21-10-1
E-25-5-B
.001
.002
.003
.004
0.0
.001
.002
Jo (emu/gm)


Magnetic Susceptibility (x10^{-5})
1.0
2.0
3.0
4.0
Distance From Rim Of E-5-5 (cm)
0
5
10
15
20
25
30
5-5-1
5-5-2
5-5-3
5-5-4
5-5-6
5-5-5
.00
.01
.02
.03
.04
.05
Jo (emu/gm)

distinct change in chemical composition. A modal analysis (Fig. 9) demonstrates that this zone is one of high glass content. The cryptocrystalline appearance of the glass suggests its high J value may be due to very fine-grained opaques as in the variolitic zones. Ilmenite and hematite in the altered zone of this pillow indicates that the magnetism may be due, at least in part, to the ilmenite-hematite solid solution series. If oxidation state alone is responsible for the variations in J through the pillow, then another high J zone should occur in the region of highest oxidation where J is, in fact, low. In this pillow at least, there is evidence that the magnetic grain size is controlling the total J.

Two cores taken normal to the pillow surface of E-21-10-1, but adjacent to a joint (Fig. 14) indicate that deuteric alteration causing serpentinization decreases J and destroys its intensity variation. The weaker J in the serpentinized zones would verify the conclusions of Cox, Doell, and Thompson (1964) who find an inverse relationship between J and degree of serpentinization. Magnetic intensity measurements across a pillow wedge below and parallel to its glass rim are also shown in Figure 14. In this case E-25-5-B1 and E-25-5-B4 contain the 6 mm. serpentine zone but the decrease in J is very slight compared to the non-serpentinized central portion.

The magnetic susceptibilities of the pillows are displayed as dashed lines along with the intensity data of Figures 12 to 15. The magnetic susceptibilities tend to increase and decrease along with the magnetic intensities except for three of the outer glass-variolite rims, E-25-5-A,C and E-15-15-B. This general correlation supports the grain-size nature of the NRM in that a very high initial susceptibility is to be expected where the grain-size is within the single magnetic domain size (Nagata, 1961, p. 28). Note the similarity in the susceptibility variation of serpentinized E-21-10-1 (Fig. 14) to E-21-10-2 (Fig. 12) and E-25-5-A (Fig. 13).

The central anomalous zone of alkalic basalt, E-5-5 (Fig. 15) has a magnetic susceptibility variation associated with it very similar to the variolitic layers of the other pillows, again, suggesting a magnetic origin in common with the variolitic zone.

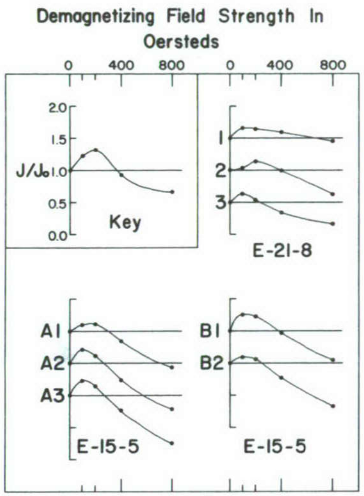
Plots of J/J_0 after demagnetizing in alternating magnetic fields shown in Figures 16 to 18 indicate magnetic components for the tholeiites which are destroyed at 50-100 H and at 250 H. The data at 0, 100, 200, 400, and 800 H treatments do not reveal much detail but treatments at increments of 50 H up to 600 H define these components. Similar plots for the alkalic basalt E-5-5 in Figure 19 also show two components, one at 50-100 H and another at 300-350 H. These

Figure 16.--Alternating Field Demagnetization Curves with Key.

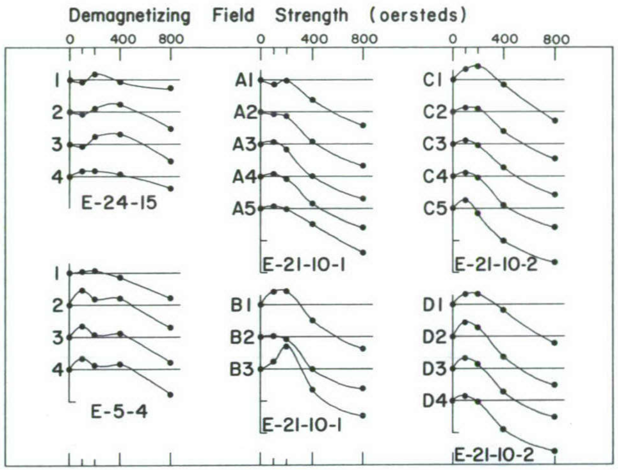
Figure 17.--Alternating Field Demagnetization Curves

Figure 18.--Alternating Field Demagnetization Curves

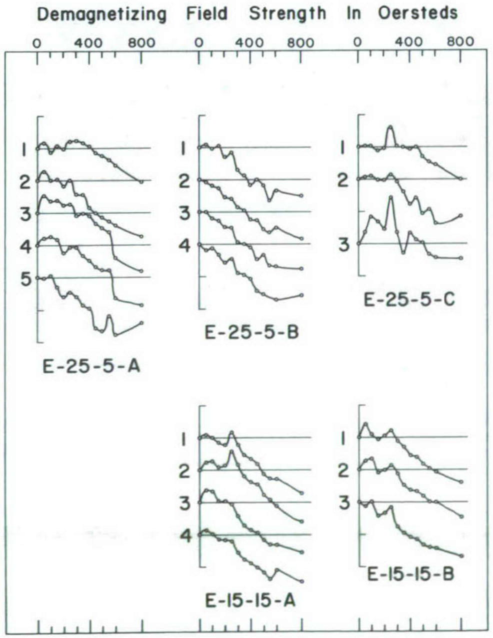
Figure 19.--Alternating Field Demagnetization Curves for E-5-5.



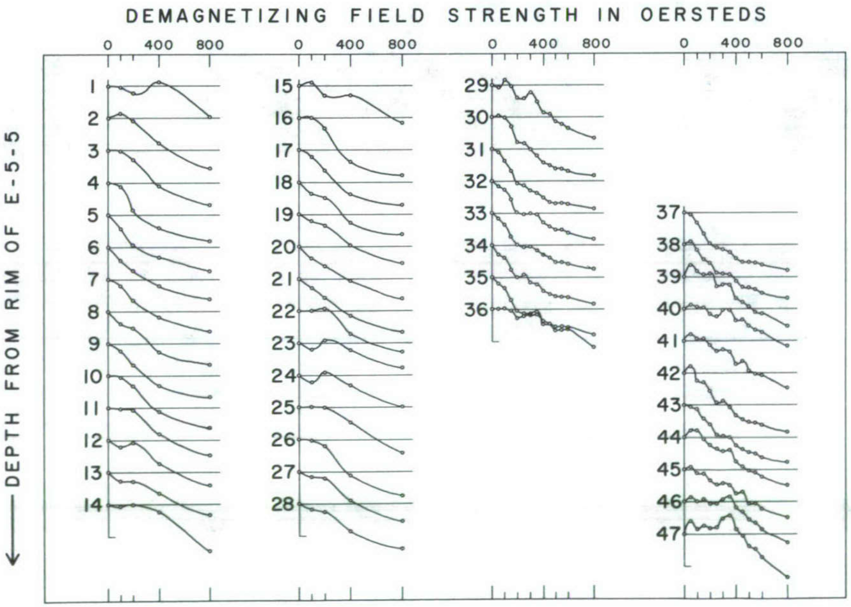
Demagnetizing Field Strength In Oersteds
0
400
800
J/J₀
2.0
1.5
1.0
0.5
0.0
Key
1
2
3
E-21-8
A1
A2
A3
E-15-5
B1
B2
E-15-5



Demagnetizing Field Strength (oersteds)
0
400
800
1
2
3
4
E-24-15
1
2
3
4
E-5-4
A1
A2
A3
A4
A5
E-21-10-1
B1
B2
B3
E-21-10-1
C1
C2
C3
C4
C5
E-21-10-2
D1
D2
D3
D4
E-21-10-2



Demagnetizing Field Strength In Oersteds
0
400
800
1
2
3
4
5
E-25-5-A
1
2
3
4
E-25-5-B
1
2
3
E-25-5-C
1
2
3
4
E-15-15-A
1
2
3
E-15-15-B



DEMAGNETIZING FIELD STRENGTH IN OERSTEDS
0
400
800
DEPTH FROM RIM OF E-5-5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

components appear to be associated with the variolitic zone at the top of the alkalic pillow and the glassy zone in the lower portion of the pillow fragment. These components are not present in the deuterically altered portion of the pillow.

The apparently weak magnetic component whose coercivity is affected in the range of 50 to 100 H does not seem to be consistent with the single domain hypothesis for the origin of the variations in J. If the variolitic zones contained magnetic minerals whose size were below that of a single-domain, then one would expect to have components whose coercivities are high. Low coercivity components have been ascribed to viscous remnant magnetism (VRM), a secondary component acquired in the earth's field after the basalt has cooled. The earth's magnetic field is thus required to affect the single-domain sized particles but not the multi-domain sized particles whose relative coercivities should be lower! On the other hand, if the low coercivity components are considered to be primary, then a single domain hypothesis is not ruled out.

In any event, it is plain that low coercivity components may appear in *only part* of a submarine pillow due to inherent differences in the properties of the magnetic minerals which are present. It is not possible, therefore, to select a sample from any one part of a pillow as being representative of the pillow. Furthermore, without additional information, it appears unreliable to relate the behavior of a single sample from a pillow in a low alternating field ($\sim$100 H) to the original polarity of the unoriented specimen as Irving and Roy (1968) have postulated.

The data indicate that initial cooling of the pillows produces magnetic minerals which acquire one or two reversed PTRM components which may be destroyed at alternating field strengths of 50 to 100 H, 250 H (tholeiites), and 300 to 350 H (alkalic basalt) while extensive deuteric alteration seems to favor minerals which do not acquire these components (e.g., E-5-5 and E-25-5).

The degree to which serpentinization affects the magnetism is uncertain, although in some samples there seems to be a weak inverse correlation.

The Iron Enigma

The petrography of the pillows indicates that iron is mobile and deposited within fractures and joints as hematite and goethite during cooling. The chemistry of the pillows indicates that the crystalline interiors of the pillows are depleted in iron relative to the unhydrated glass and variolitic zones by as much as 2.0% of the total rock weight or roughly 20% of the total iron.

The chemical analyses show that the major part of the total iron discrepancy is in the ferrous iron. If iron is most mobile in its ferrous state, then low oxygen fugacities are required, otherwise magnetite would crystallize. Low oxygen fugacities are to be expected in the pillows considering the relatively rapid rate of cooling which the pillows must have undergone. Hamilton, Burnham, and Osborn (1964) showed that the lowest oxygen fugacity at which magnetite is stable using a buffer of magnetite + wustite + water is 10^{-11} atmospheres at 1100°C. and drops to 10^{-28} at 500°C.

An order of magnitude figure for the length of time required for the interior of a 30 cm. diameter pillow to cool from 1100°C. to 500°C. is 1.5 hours (Jaeger, 1968). Because the effect of joints on the rate of cooling is not known, 1.5 hours is probably an upper limit. It is certain that jointing occurs after significant crystallization of the major mineral phases. The influence of joints on cooling rates may not even be significant. The small amount of water entering a newly formed joint approximately 0.3 mm. in width would have to overcome effusing vapors. The exchange of heat at the pillow surface between 0.3 mm. fractures and cold sea water would be only a small fraction of the heat dissipated from the joint surfaces were they directly exposed to freely circulating sea water.

It is assumed that the pillows did not pick up appreciable amounts of sea water for the following reasons:

1. The maximum solubility of water in the lava is about 1.5% H_2O or equal to the maximum value found in unhydrated glass.
2. The pillow zones below the glass contain less water than unhydrated glass which is believed to be due to dehydration during cooling.
3. The deuteric serpentine zones which was formed in the presence of excess water is found within 6 mm. of the joints and fractures and rarely deeper within the pillows.

The work of Bernal, Dasgupta, and MacKay (1959) indicates that at low temperatures and pressures, ferrous hydroxide compounds are not sufficiently soluble to be transported by water in the concentrations required to deplete the pillows. The stability field relationships of the ferrous compounds at high temperatures and pressures may be favorable to high iron solubilities, but, at present, there is no available evidence to support any process involving excessive amounts of water as the transporting agent.

Krauskopf (1957) has presented thermodynamic arguments indicating that to account for a loss of 2% iron by vapor transport the amount of volatiles needed at 600°C. and 1000 atmospheres would be on the order of 10,000 cm.^{3} volatiles per 1 cm.^{3} of pillow basalt. This figure does not seem at all practicable and it seems highly unlikely that new thermodynamic information could bring a simple method of vapor transport into the realm of feasibility.

That this problem is not confined to tholeiites is shown by the similar results for the analyses of the alkali basalt and analyses of a quartz monzonite of the Iron Springs District of Utah reported by Mackin (1947). Mackin found a depletion of iron in the interior of the jointed Three Peaks intrusion relative to the "fresh" peripheral shell of the body and he discussed the concentration of magnetite crystals in the joints. He ascribed the iron movement to deuteric alteration. Unfortunately, his data shed no light on the present problem although a similar mechanism appears to operate in both types of rock.

Zelenov (1964) has described volcanic exhalations from an andesite-dacite submarine volcano in Indonesia. The last eruption ended in 1919, but in 1963, diving on the submerged summit disclosed continuous gaseous and hot water jets emanating from fissures in the rock outcrop. The rock showed no hydrothermal alteration in thin section and was too hot to handle 20 cm. beneath the outcrop surface.

The most pertinent aspects of Zelenov's descriptions are the chemical constitutents of the exhalations. Analyses of samples from the mouths of the hot water jets yielded 100 to 140 mg. of iron and manganese per liter of water. The hot water issuing from fissures is initially colorless but becomes turbid about one meter above the bottom due to the precipitation of iron and manganese hydroxides. Much of the hydroxides is swept away by currents but some accumulates on the ocean floor around the fissures. Analyses of this dried precipitate yielded Fe_2O_3 + FeO up to 46%, MnO + MnO_2 to 7%, P_2O_5 to 2.7%, TiO_2 to 0.25%, SiO_2 to 12%, Al_2O_3 to 4%, H_2O to 7% and sea water salts about 25%. Analysis of the gas jets yielded 96.97% CO_2, 2.86% N, a trace of CH_4, He and Ar. No oxygen or hydrogen were detected which may indicate low oxygen fugacities.

Zelenov's report strengthens the case for high mobility of iron in volcanic rocks in the submarine environment and it seems possible that the exhalations which he reports are products of the same type of deuteric alteration found in the pillow basalts.

Based on the foregoing discussion the probable conditions under which iron migrates out of submarine pillows are as follows:

1. Temperature between solidus of silicate phases (1100°C.) and serpentinization (400°C.).
2. Water content about 1.5% by weight or less.
3. Oxygen fugacity from 10^{-11} atmospheres at 1100°C. to 10^{-28} atmospheres and lower at lower temperatures.
4. Iron escapes in its ferrous state.
5. The mechanism is not dependent upon the bulk chemistry of the rock except, of course, for an initial iron content. The rate may be dependent upon many factors, however.
6. The time required can be as short as 1.5 hours in the case of tholeiite for the total temperature range from 1100°C. to 400°C.
7. The system must be partially open (e.g., jointed) to provide an effective concentration gradient whereby iron may move. This movement appears to be facilitated if the joints are accessible to water.

Whatever the ultimate cause of iron depletion in submarine pillows the results are impressive. A conservative estimate of the quantity of iron released from the center of a spherical pillow 30 cm. in diameter, of specific gravity 2.7, and 1.0% FeO depletion, would be on the order of 130 gm. Fe. Undoubtedly most of this iron remains in joints and fractures as oxidation products but the potential source of iron is vast enough to account for the anomalously high accumulations in deep-sea clays and ferromanganese concretions.

Representative Sampling

In the following discussion a normative percentage of 0.0% quartz and 0.0% olivine is termed saturated; whereas quartz in the norm or olivine in the norm are termed oversaturated or undersaturated, respectively.

Nicholls, Nalwalk, and Hays (1964) and Yoder and Tilley (1962, p. 375) have noted that alteration of basalt resulting in hydration and iron oxidation tends to produce silica oversaturated tholeiitic rocks from normative undersaturated rocks. It is not surprising therefore that the normative analyses of the *Eltanin* tholeiites show similar trends from undersaturation in the variolitic and unhydrated glass zones to silica saturation in the hydrated zones. What is apparent in these tholeiites is a definite reversal in trend from the undersaturated variolitic zones toward saturation in the interior of the pillows.

Seven of the eight tholeiitic pillows show this reversal in trend. The interior saturation is attributed to the loss of iron and magnesium and the oxidation of iron. The Larsen diagrams indicate this trend inasmuch as the formula 1/3 SiO_2 + K_2O - (FeO + MgO + CaO) is a mafic (or salic) index. The higher (more positive) this index, the more salic is the rock. Thus, the hydrated glasses are on the right side of the diagram (Fig. 11) due to the loss of magnesium and calcium and the increase in potassium (saturated), the variolitic zones plot on the left side (undersaturated), and the lithic interiors are again on the right side of the diagram (Fig. 7). The eighth tholeiitic rock, E-24-15, is slightly oversaturated and does not quite reach saturation in the variolitic zone. This may be due to the deep penetration of hydration in this sample. In view of these results, tholeiite analyses of glass and variolitic zones containing greater than 2.0% total water should be viewed with suspicion.

It appears that the most representative analyses of pillows are those of unhydrated glass and variolitic zones. Except for extreme hydration the alteration which has the greatest effect on the analyses is that involving the loss and oxidation of the iron as can be seen in Table 2, therefore, as a "best estimate" analyses involving slightly more than 2.0% water are included as "most representative." The result is that the slightly hydrated samples contain anomalously high potash values but errors in the iron and magnesium are minimized. It is obvious that from a purely chemical standpoint very few of the analyses are ideal.

E-24-15 was thoroughly hydrated; but the remaining seven most representative analyses of the tholeiites were adjusted (when slightly hydrated) by replacing their potash percentages with the average potash of their respective analyses containing less than 2.00% total water. The analyses were then recalculated water free and averaged as displayed in Table 3. The analyses used are those for which the norms are shown in Table 4.

The Primitive Basalt Problem

When the average of the *Eltanin* samples is compared with the average of eight tholeiites from the Mid-Atlantic Ridge reported by Muir and Tilley (1966) the similarity is evident (Table 3). The differences in silica and alumina may be due, in part, to analytical techniques but the accuracy of the alumina is sufficient to show a lower alumina value than that reported by Engel et al. (1965), and therefore, the present writer agrees with Muir and Tilley that the high alumina tholeiites implied by Engel et al. (1965) may not be representative of the ocean floor. The higher silica and lower alumina values for the *Eltanin* tholeiites, if real, may reflect differences between the Mid-Atlantic Ridge and the deeper parts of the South Pacific basin but this is clearly only a tentative observation. The low potash values previously reported for oceanic tholeiites is verified in the *Eltanin*

TABLE 3

AVERAGES OF THOLEIITIC ROCKS FROM OCEANIC AND CONTINENTAL PROVINCES
(Recalculated water free)

	1	2	3	4	5
SiO_2	50.5	50.06	49.94	49.17	51.4
Al_2O_3	14.9	15.35	17.25	15.50	13.9
Fe_2O_3	1.55	2.19	2.01	2.90	3.9
FeO	8.70	8.48	6.90	8.59	9.3
MgO	7.39	7.80	7.28	8.64	5.3
CaO	11.28	11.14	11.86	10.68	9.9
Na_2O	2.80	2.78	2.76	1.87	2.8
K_2O	.20	.18	.16	.13	1.1
TiO_2	1.68	1.63	1.51	2.12	1.8
P_2O_5	.15	.13	.16	.22	.3
MnO	.15	.18	.17	.18	.3

1. Average of seven _Eltanin_ tholeiites, this paper.
2. Average of eight Mid-Atlantic Ridge tholeiites (Muir and Tilley, 1966).
3. Average of ten oceanic tholeiites (Engel et al.,1965).
4. Average of thirteen tholeiites, Pololu Series, Kohala Mt., Hawaii (Macdonald and Katsura, 1964, Table 9, Analysis 5).
5. Average of eight tholeiitic basalts from the Hebridean Province (Turner and Verhoogen, 1960, p. 226).

tholeiites although E-5-4 appears to be transitional in potash content. An average of eight continental tholeiites from the Hebridean Province of Mull (Turner and Verhoogen, 1960, p. 226) are included in Table 3 for comparison. The higher potash percentage for these rocks is typical of the continental variety of tholeiitic rocks. The silica and alumina percentages for the Eltanin tholeiites fall between the values of other oceanic tholeiites and the Hebridean Province tholeiites. The lower ferric iron content of the Eltanin tholeiites is due to the lower oxidation state of the iron in the glass and variolitic layers of the pillows.

The only obvious similarity between the averages of 13 primitive tholeiites from the Pololu series of Kohala Mt., Hawaii, and the oceanic rocks is the low potash percentage. The Na_2O percentage is anomalously low and the titanium and phosphorous values are within a higher range common to oceanic island tholeiites.

When the best estimated analysis of each tholeiite in this study is selected for comparison in the norm, they are found to have compositions which are very similar (Table 4)

The potash was not corrected for the normative computations of Table 4 and therefore, in some cases, give erroneous orthoclase norms, but errors in the more essential normative minerals such as diopside and hypersthene are minimized.

TABLE 4

NORMS OF MOST REPRESENTATIVE ANALYSES OF
ELTANIN PILLOWS

Sample	Or	Ab	An	Di	Hy	Ol	Mt	Il	Ap
5-4-1	2.40	22.98	24.91	23.42	18.51	.65	2.71	3.99	.43
15-5-1	1.36	23.30	27.40	23.00	16.37	3.25	2.26	2.73	.33
15-15-1	.76	23.72	27.19	24.64	15.16	2.98	2.53	2.69	.33
21-8-1	2.16	23.38	23.53	20.84	19.53	4.17	2.01	3.96	.42
21-10-1-1	.70	24.08	27.18	23.33	14.64	4.29	2.39	3.02	.37
21-10-2-1	.58	22.54	29.99	21.63	16.65	4.48	1.35	2.48	.30
25-5-1b	2.84	24.11	27.60	19.20	18.74	1.46	2.42	3.27	.36

It may be significant that these tholeiites are just undersaturated in the norm, containing a slight amount of olivine in contrast to many submarine basalts dredged from oceanic ridges or submarine escarpments which vary widely in olivine content. Table 1 shows that most of the Eltanin tholeiites were collected from areas of the deep sea floor with 550 meters relief or less. Olivine tholeiites produced by the gravity settling of olivine would commonly be dredged from regions of rugged bathymetry such as the Mid-Atlantic Ridge (Muir et al., 1964) where they are brought to the sea floor surface through faulting or where magma reservoirs might be large enough to allow appreciable olivine accumulates to segregate. An alternative interpretation in the tholeiite - olivine tholeiite association would be that the tholeiites of the abyssal hills originate at a shallower depth than do the olivine tholeiites though the parental material would be the same (Yoder and Tilley, 1962, p. 411). One would then attribute the magmatic source of oceanic regions of high relief as lying, at least in part, at greater depths than that of abyssal hills.

If these deep ocean tholeiites are considered to be the primary tholeiite from which alkalic basalts are produced then one must explain how silica deficient alkalic basalt may be produced from them inasmuch as fractional crystallization would, in all cases, lead to silica enriched differentiates (Yoder and Tilley, 1962, p. 427). If these deep ocean tholeiites are not considered to be the primary lava but one step in the differentiation sequence then differentiation would not necessarily occur in association with elevated regions such as seamounts or oceanic ridges.

The suggestion that alkalic basalts are generated at a greater depth in the mantle than tholeiites appears to be the best explanation, thus far, for the origin of the two basalt types. The observation that alkalic basalts are associated with seamounts as opposed to the abyssal floor, if true, would then suggest either a greater volume of extrusion from seamounts or a more viscous lava which builds a pedestal more rapidly. At present the evidence is meager that alkalic basalts are generated by some obscure process in the elevated conduits of seamounts as has been suggested (Engel et al., 1965). The possibility that seamounts may be generated by alkalic basalt eruptions is just as likely.

CONCLUSIONS

Pahoehoe toes, pillows, and hyaloclastites which are found at abyssal depths can be explained as different products of an eruption similar to the pahoehoe type.

The vesicularity of the pillows from depths of 3200 meters to 4800 meters is less than 3% indicating that the lavas were not greatly oversaturated in volatiles when they solidified. Their low vesicle content and H_2O contents of less than 2.0% are in agreement with the values predicted from considerations of temperature, pressure, and water solubility in basaltic melts. Higher vesicularities at these depths in the Eltanin samples are attributed to voids left from the deuteric alteration of olivine and contamination with sea water.

Three types of chemical alteration have been found in the submarine tholeiite pillows:

1. Hydration (palogonitization) of the basaltic glass, found to be greater than 2.0% total H_2O, results in a decrease in calcium and magnesium and an increase in total iron, ferric/ferrous ratio and potassium. Hydrated glass commonly contains phillipsite and a subordinate amount of montmorillonite.

2. Serpentinization, a form of deuteric alteration, occurring below 400°C., is associated with an excess of water resulting in the conversion of olivine to serpentine in zones averaging 6 mm. thick on each side of joints and fractures.
3. Chloritization, a higher temperature deuteric alteration (400°C. - 1100°C.), occurs at the concentration of volatiles originating within the lava. This alteration produces trace amounts of chlorite, talc, hematite and magnesite in the interior, aphanitic portion of the pillows. Olivine may be replaced in some instances but this is not always apparent. A major result of this alteration is a depletion of the interior of pillows by as much as 20.0% of the total FeO present with migration of the iron to joints, fractures, and vesicles where it is oxidized to hematite and goethite.

From the chloritization type of alteration it is estimated that a spherical pillow 30 cm. in diameter releases a minumum of 130 gm. of iron. If one considers the quantity of volcanics on the ocean floor, this process could release a prodigious amount of iron into the submarine environment. Such a process may account for the high iron content of "red" clays and ferro-manganese concretions.

The magnetic parameters of intensity, susceptibility and the unstable magnetic components of the pillows can, in most cases, be correlated with the size of the opaques and deuteric alterations.

In spite of the chemical alterations it is possible to select a chemically representative sample of basalt from the unhydrated glass or variolitic zones of the pillows. Remarkably similar chemistry is found in these zones for all but one tholeiite. Normative analyses of these zones are all slightly undersaturated with an olivine content of less than 4.48% by weight. One tholeiite hydrated throughout contains 2.17% quartz in the norm. The association of the tholeiites with abyssal hills and rises of the Southern Ocean and their nearly identical composition suggests that they are representative flood basalts of the deep ocean floor where bathymetric relief is not much more than 550 meters.

APPENDIX A

DIFFERENCES BETWEEN DUPLICATE CHEMICAL DETERMINATIONS

Sample #	SiO_2	Al_2O_3	MgO	CaO	Na_2O
5-4-1a	0.6	0.0	.16	.31	.02
5-4-1	0.4	0.1	.38	.57	.14
5-4-2-	0.1	0.1	.07	.06	.02
5-5-1	0.3	0.0	.36	.34	.07
5-5-2	0.1	0.1	.01	.03	.05
5-5-3	0.6	0.1	.07	.02	.09
5-5-4	0.3	0.2	.07	.01	.08
5-5-6	0.2	0.1	.05	.10	.07
5-5-5	0.3	0.1	.07	.07	.06
15-5-1	0.3	0.0	.08	.02	.03
15-5-2	0.5	0.0	.05	.13	.03
15-15-1	0.2	0.0	.01	.08	.06
15-15-2	0.3	0.2	.01	.21	.04
21-8-1	0.5	0.1	.04	.16	.11
21-8-2	0.3	0.1	.04	.15	.02
21-8-3	0.1	0.2	.09	.48	.07
21-10-1-1	0.4	0.2	.08	.28	.01
21-10-1-2	0.4	0.2	.00	.04	.05
21-10-2-1	0.1	0.2	.04	.12	.10
21-10-2-2	0.1	0.4	.00	.04	.01
24-15-1	0.3	0.1	.06	.17	.01
24-15-2	0.1	0.0	.07	.02	.03
24-15-3	0.2	0.1	.00	.29	.03
25-5-1a	0.1	0.0	.05	.09	.11
25-5-1b	0.3	0.1	.27	.04	.03
25-5-2	0.3	0.1	.20	.27	.07
25-5-3	0.3	0.0	.08	.01	.00

*Denotes maximum value obtained from six standard runs.

APPENDIX A--Continued

K_2O	H_2O^{+*}	H_2O^{-*}	TiO_2	P_2O_5	MnO	FeO^*	Total Fe as Fe_2O_3
.07	---	---	.14	.02	.01	---	.01
.02	.03	.02	.10	.01	.01	.20	.17
.00	.03	.02	.00	.02	.01	.20	.18
.08	.03	.02	.15	.05	.01	.20	.05
.02	.03	.02	.10	.01	.01	.20	.18
.01	.03	.02	.08	.03	.01	.20	.16
.04	.03	.02	.10	.03	.01	.20	.11
.04	.03	.02	.06	.03	.00	.20	.35
.00	.03	.02	.06	.03	.00	.20	.09
.00	.03	.02	.04	.01	.00	.20	.08
.00	.03	.02	.04	.00	.01	.20	.06
.02	.03	.02	.05	.00	.00	.20	.18
.00	.03	.02	.05	.01	.01	.20	.20
.01	.03	.02	.05	.00	.02	.20	.17
.01	.03	.02	.06	.01	.02	.20	.17
.01	.03	.02	.11	.01	.00	.20	.42
.02	.03	.02	.01	.00	.01	.20	.33
.01	.03	.02	.01	.00	.01	.20	.28
.00	.03	.02	.03	.00	.00	.20	.01
.02	.03	.02	.01	.00	.01	.20	.04
.01	---	.02	.02	.02	.00	.20	.34
.00	.03	.02	.03	.00	.01	.20	.11
.00	.03	.02	.03	.01	.03	.20	.01
.03	.03	.02	.02	.01	.02	.20	.12
.01	.03	.02	.04	.01	.01	.20	.13
.00	.03	.02	.01	.01	.01	.20	.30
.00	.03	.02	.02	.02	.01	.20	.19

APPENDIX B

MAGNETIC PARAMETER VALUES OF *ELTANIN* SUBMARINE PILLOWS

J (EMU/gm) AFTER TREATMENT IN ALTERNATING FIELD OF H

Specimen No.	Magnetic Susceptibility (x 10^{-6})	J_0	J_{100}	J_{200}	J_{400}	J_{800}
E-5-4-1	7.08	.005677	.005815	.005875	.005261	.003457
2	8.05	.010354	.012675	.011286	.011411	.006751
3	8.15	.013090	.015343	.013548	.013863	.007903
4	7.05	.009231	.010855	.009762	.009926	.005572
E-5-5-1	10.0	.001955	.001912	.001744	.002097	.001005
2	21.9	.051047	.054900	.049139	.031038	.011334
3	17.6	.027394	.027289	.023394	.012301	.004173
4	16.0	.023629	.022396	.013563	.006995	.002153
5	24.1	.016626	.013023	.008793	.005429	.002011
6	22.6	.013394	.010511	.008502	.005235	.002449
7	23.1	.011921	.010563	.007937	.004842	.002154
8	25.0	.012344	.009925	.009138	.004441	.001985

APPENDIX B.--Continued

E-5-5-9	25.4	.014466	.012781	.009514	.004997	.002352
10	38.5	.021558	.021000	.017787	.009438	.004015
11	27.1	.018354	.017939	.017567	.010703	.004634
12	15.6	.018375	.016445	.017477	.011504	.005512
13	11.7	.013906	.012050	.011834	.009190	.004714
14	13.2	.020884	.020287	.020749	.018341	.005738
15	17.5	.035537	.037304	.030188	.030331	.014920
16	22.1	.033925	.033946	.028083	.011082	.003455
17	18.7	.018566	.016692	.012661	.005834	.002652
18	22.1	.015728	.012926	.011796	.005859	.002966
19	21.9	.012001	.010689	.009888	.006213	.002842
20	27.7	.013299	.010966	.009279	.006139	.002426
21	26.7	.014849	.012601	.010346	.006211	.002340
22	31.8	.016055	.016025	.016468	.010368	.005714
23	32.4	.017512	.015684	.018002	.015525	.010676
24	19.7	.018988	.016945	.019810	.016035	.009593
25	14.8	.022030	.022288	.022213	.016690	.006152
26	18.5	.024921	.024626	.022159	.010994	.002954
27	14.1	.013175	.012163	.011857	.007254	.002901
28	13.4	.011458	.010331	.009920	.006499	.003370

APPENDIX B.--Continued

Specimen No.	Magnetic Susceptibility (x 10^{-6})	J_0	J_{100}	J_{200}	J_{400}	J_{800}
E-15-5-A1	6.23	.007587	.008383	.008149	.006426	.003271
A2	7.34	.008502	.010277	.009370	.006254	.002415
A3	7.93	.005933	.007299	.006807	.004522	.001336
E-15-5-B1	5.00	.004467	.005593	.005467	.004354	.002454
B2	7.84	.011200	.012161	.011842	.008577	.003642
E-21-8-1	10.2	.004358	.005017	.005002	.004725	.004143
2	9.10	.003481	.003602	.003971	.003424	.002170
3	7.72	.000799	.000902	.000821	.000678	.000531
E-21-10-1-						
A1	7.38	.001959	.001830	.001921	.001363	.000571
A2	9.52	.002050	.001986	.001901	.001108	.000329
A3	8.12	.001880	.001961	.001734	.000966	.000291
A4	8.35	.002172	.002262	.002069	.001252	.000448
A5	8.68	.002055	.002110	.002031	.001561	.000643

APPENDIX B.--Continued

E-21-10-1						
B1	7.37	.002530	.003043	.003068	.001926	.000781
B2	8.44	.002416	.002459	.002356	.001221	.000477
B3	8.61	.002176	.002451	.002962	.001474	.000585
E-21-10-2-						
C1	5.91	.006525	.007615	.007868	.006025	.002351
C2	7.27	.008957	.009563	.009432	.006310	.002455
C3	7.50	.007313	.007735	.007206	.004676	.001494
C4	8.06	.008008	.008484	.007874	.004391	.001626
C5	11.61	.010381	.011706	.009575	.005186	.001608
E-21-10-2-						
D1	4.58	.003882	.004508	.004526	.003567	.001540
D2	8.68	.009299	.011320	.010657	.006383	.002253
D3	7.89	.006810	.008001	.007308	.004370	.001689
D4	10.92	.011135	.011859	.010915	.005608	.002242
E-24-15-1	8.82	.001714	.001638	.001852	.001649	.001482
2	12.1	.002829	.002735	.002987	.003179	.002063
3	11.8	.002925	.002842	.003270	.003386	.002128
4	9.87	.001931	.002117	.002109	.002009	.001567

APPENDIX B.--Continued

Specimen No.	Magnetic Suscepti- bility (x 10^{-6})	J_0	J_{50}	J_{100}	J_{150}	J_{200}	J_{250}	J_{300}
E-5-5-29	19.2	.047426	.045499	.051212	.046461	.038502	.037860	.041928
30	19.9	.034728	.035527	.034575	.029730	.020981	.020372	.017284
31	22.4	.024893	.023741	.020385	.016285	.011424	.010748	.008712
32	23.5	.014581	.013376	.012780	.010389	.007389	.006997	.007161
33	23.3	.013261	.012101	.010897	.008359	.006706	.006190	.006298
34	27.3	.012801	.010912	.010232	.007774	.006368	.006804	.005284
35	30.3	.016207	.014558	.013458	.010473	.007714	.006982	.007057
36	28.7	.013662	.013768	.013891	.013374	.011751	.012108	.012718
E-5-5-37	29.6	.011209	.010942	.009443	.007491	.005835	.005014	.004817
38	28.5	.012894	.013566	.011788	.009976	.009146	.007212	.007118
39	30.9	.018292	.021756	.019824	.018993	.019208	.015526	.016040
40	22.8	.022340	.023727	.023158	.022809	.020383	.019622	.021959
41	15.9	.023266	.025669	.024128	.024170	.021840	.019571	.020153
42	16.3	.025992	.028601	.022732	.022189	.018476	.014093	.014707
43	15.0	.013486	.013181	.012567	.010611	.009387	.007266	.007005
44	14.8	.009536	.010548	.010546	.009173	.008344	.007707	.007423
45	16.1	.010855	.011130	.010178	.010031	.008864	.008206	.008487
46	13.4	.014853	.015792	.014800	.015292	.014421	.014380	.015347
47	13.4	.017643	.021060	.018895	.019727	.019143	.019392	.021764

APPENDIX B.--Continued

E-15-15-A1	9.18	.009800	.010262	.009767	.009070	.008740	.010638	.008759
A2	7.37	.006984	.007785	.007945	.007315	.007480	.008970	.007547
A3	7.59	.004218	.005025	.004878	.004299	.004268	.004078	.003326
A4	7.60	.003709	.003947	.003716	.003427	.003381	.003316	.002658
E-15-15-B1	4.82	.007515	.009033	.007902	.007221	.007651	.008311	.007049
B2	7.91	.007354	.008414	.008581	.006966	.007311	.007820	.006926
B3	7.77	.002837	.002667	.002864	.002247	.002365	.002324	.001743
E-25-5- A1	6.58	.002412	.002615	.002277	.002512	.002393	.002666	.002700
A2	9.65	.001948	.002222	.001957	.002002	.001767	.001937	.001528
A3	8.34	.000832	.001049	.000985	.000996	.000932	.000946	.000788
A4	8.17	.000758	.000836	.000859	.000823	.000666	.000730	.000725
A5	7.79	.001028	.001020	.001048	.000873	.000723	.000790	.000622
E-25-5- B1	7.64	.001354	.001414	.001319	.001383	.001148	.001231	.000878
B2	8.46	.001713	.001634	.001547	.001471	.001240	.001204	.000985
B3	8.58	.001913	.001904	.001721	.001639	.001455	.001441	.001027
B4	8.23	.001597	.001444	.001506	.001332	.001136	.001233	.000885
E-25-5- C1	7.98	.002651	.002676	.002681	.002495	.002600	.003449	.002677
C2	9.75	.001943	.001998	.002041	.001918	.001899	.002077	.001870
C3	9.39	.000810	.000954	.001149	.001087	.000989	.001383	.000954

APPENDIX B.--Continued

Specimen No.	Magnetic Suscepti- bility (x 10^{-6})	J_{350}	J_{400}	J_{450}	J_{500}	J_{550}	J_{600}	J_{800}
E-5-5-29	19.2	.035122	.026964	.026065	.020697	.018662	.015476	.008175
30	19.9	.013788	.009869	.008622	.006680	.006310	.005336	.002921
31	22.4	.007743	.005849	.004237	.003815	.003826	.003528	.001437
32	23.5	.006955	.005130	.004301	.003523	.003372	.002693	.001429
33	23.3	.005485	.004632	.003991	.003064	.003120	.002726	.001666
34	27.3	.004887	.003611	.002940	.002560	.002550	.002352	.000957
35	30.3	.006629	.005051	.004362	.003621	.003646	.003358	.001667
36	28.7	.013122	.010544	.010543	.009054	.009152	.008060	.005492
E-5-5-37	29.6	.004343	.003196	.002596	.002512	.002424	.002042	.001135
38	28.5	.006984	.005531	.004441	.004297	.003993	.003272	.002160
39	30.9	.015986	.012141	.011073	.009759	.008300	.007852	.004264
40	22.8	.021857	.018243	.018619	.016382	.014831	.014246	.009286
41	15.9	.019264	.015075	.013653	.012414	.011295	.010807	.006002
42	16.3	.012029	.008741	.007108	.006124	.005740	.005017	.002036
43	15.0	.006724	.004915	.004183	.003492	.003371	.002380	.001461
44	14.8	.007679	.005856	.005191	.004568	.004286	.003627	.002432
45	16.1	.008101	.006695	.005948	.005045	.005084	.004123	.002686
46	13.4	.015919	.013349	.012478	.010603	.009913	.008281	.005378
47	13.4	.022503	.018721	.017047	.014106	.013339	.011098	.005685

APPENDIX B.--Continued

E-15-15-A1	9.18	.007207	.006617	.005801	.004264	.003581	.003499	.001344
A2	7.37	.006300	.005681	.005411	.004348	.003743	.003062	.001415
A3	7.59	.002711	.002400	.002210	.001759	.001464	.001425	.000954
A4	7.60	.002258	.002062	.001812	.001510	.001164	.001664	.001004
E-15-15-B1	4.82	.006392	.005418	.005240	.004401	.003861	.003556	.002233
B2	7.91	.005549	.005056	.004853	.004383	.003662	.003636	.001982
B3	7.77	.001473	.001284	.001187	.000965	.000843	.000808	.000441
E-25-5- A1	6.58	.002598	.002494	.002252	.002132	.001984	.001754	.001171
A2	9.65	.001327	.001129	.000972	.000847	.000726	.000596	.000276
A3	8.34	.000825	.000789	.000695	.000640	.000588	.000246	.000082
A4	8.17	.000638	.000577	.000504	.000462	.000463	.000135	.000060
A5	7.79	.000578	.000537	.000221	.000177	.000416	.000112	.000303
E-25-5- B1	7.64	.000756	.000552	.000675	.000560	.000548	.000453	.000344
B2	8.46	.000881	.000647	.000627	.000392	.000317	.000422	.000157
B3	8.58	.000956	.000862	.000501	.000649	.000350	.000283	.000218
B4	8.23	.000841	.000735	.000442	.000358	.000255	.000227	.000330
E-25-5- C1	7.98	.002657	.002561	.002641	.002250	.002039	.001940	.001334
C2	9.75	.001535	.001188	.001386	.000901	.001050	.000611	.000828
C3	9.39	.000692	.000953	.000858	.000820	.000273	.000238	.000618

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