

# *Mechanisms of Deep-sea Volcanism in the South Pacific*

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## Introduction

Recently data on volcanism within the Pacific basin have greatly increased, as may be seen from a summary of our present knowledge made by Menard (1964). Still, the modes of activity of deep-sea volcanoes are unclear in many aspects, one reason for this being the difficulty with which routinely precise and complete samplings of hard rocks can be carried out through thousands of meters of water, using the equipment we currently have available.

There are reasons to believe that the medium in which the volcanic activity takes place often has a great influence on the mechanisms and products involved. That is, quite a different set of rocks will generally be formed by the same magma, depending on whether it is extruded subaerially or at depth under the sea.

In this chapter a study of rocks collected at six deep-sea volcanic sites in the southeast Pacific is presented. Such rocks are all of basaltic composition, but their petrology indicates that the submarine eruptions responsible for their emplacement are of two types. In one type of eruption the lava appears to have flowed quietly on the ocean floor, any significant interaction with seawater being prevented by the instantaneous formation of a thin insulating crust of glass at the surface of the flows. Rocks resulting from such activity show features similar to subaerial "pahoehoe," and occasionally are pillow lavas. Lavas produced by quiet effusions appear to be preferentially associated with hilly bottom topography and to be derived from fissure-type eruptions. Submarine volcanism of this type does not affect notably the chemistry

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of the ocean floor outside of those areas directly covered by the lava flows.

In the other mechanism of eruption (called here "hyaloclastic") there is, on the contrary, evidence of extensive physical and chemical interaction between the hot lava and sea water during the outbreak. Much of the lava has been shattered and pulverized from coming into contact with seawater and being chilled rapidly. The resulting lava debris (hyaloclastites) is rapidly hydrated at high temperature, forming mainly palagonitic glass. At the same time chemical leaching by seawater causes the loss from the lava fragments of quantities of various elements, some of the ferrides, for instance, which are subsequently partly fractionated and precipitated, thereby strongly influencing the chemistry of the ocean floor in the vicinity of the outbreak. Hyaloclastic volcanism also influences the mineralogy of areas adjacent to the eruption; the finest volcanic debris is scattered in wide areas around the parent volcano and gradually altered to zeolites and smectites. Hyaloclastic volcanism in the south Pacific seems to be connected preferentially with sea mounts, and is probably important in the building up of these structures.

The depth below sea level at which the activity takes place apparently does not determine whether the eruption follows one or the other mechanism. It is suggested that one of the main factors determining whether a submarine basaltic lava will undergo quiet or hyaloclastic eruption is its viscosity at the time of ejection into the water. Very hot, fluid melts appear to erupt "quietly," while more viscous lavas form hyaloclastites.

Discussion of the processes mentioned above is based on a study of lavas collected by chain dredge from the R. V. *Argo* during the first leg of the Scripps Institution of Oceanography's expedition "Amphritrite." A restudy of some material collected by the 1873-1876 "Challenger" expedition is also included.

### Presentation of Field and Laboratory Data

Table 1 gives a schematic summary of the data, which are presented below in more detail. The approximate position of the stations is shown in figure 1.

#### Station Amph D1

Some hundred kilograms of rocks were recovered from a sea mount close to the crest of the East Pacific Rise. A profile of the bottom obtained at this location with a precision depth recorder (PDR) is reported

in figure 2. Additional crossings show that the two reliefs are two nearby sea mounts and not part of a double ridge.

The dredge haul consists of the following.

1. More than 80 per cent of the material consists of boulders and fragments of various sizes of a porphyritic basalt in which phenocrysts of a fresh plagioclase up to half a centimeter in size are visible in hand specimens. Under the microscope the phenocrysts appear to be in the labradorite-bytownite range and are contained in a groundmass of tiny laths and needles of plagioclase, altered femics, and glass, the whole

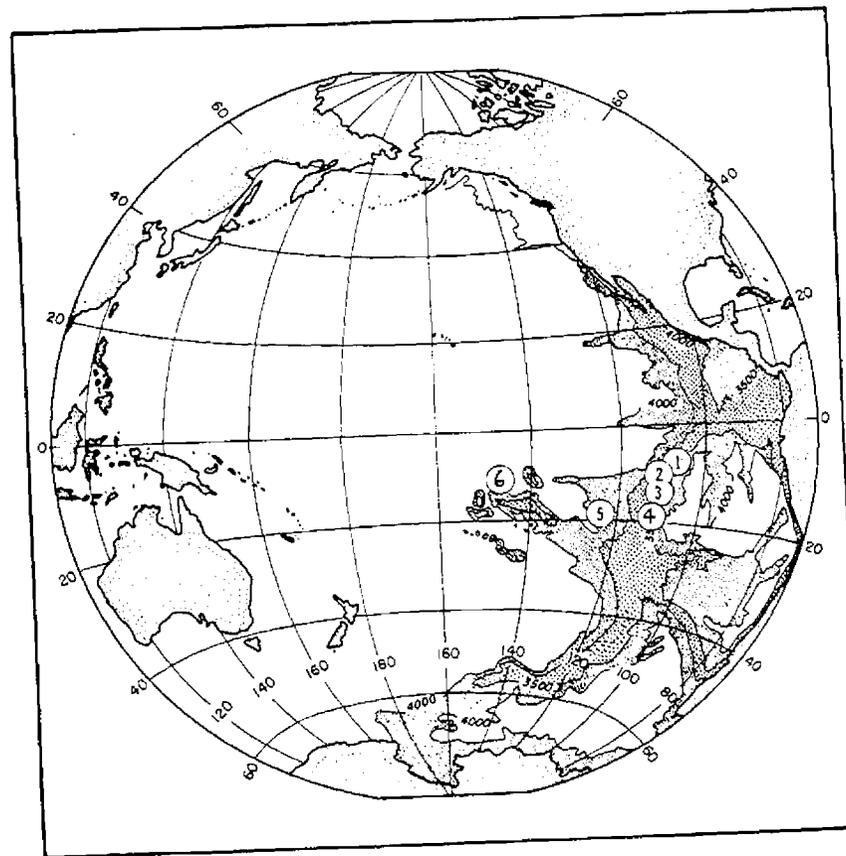


Fig. 1. Map of the Pacific Ocean with a profile of the East Pacific Rise as given by the 3500- and 4000-meter isobaths. Location of stations studied in the present paper are indicated: 1 is Amph D1; 2 is Amph D2; 3 is Amph D3; 4 is Amph D4; 5 is survey area Amph D5 (see detailed map in figure 9); 6 is Chall 276.

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TABLE 1. Summary of Data on the Sites of Deep-sea Volcanism Reported in the Present Paper\*

Station	Location	Type of bottom	Depth	Type of rocks recovered
Amph D1	7°50'S 108°08'W	Sea mount	1570-2020 m	Massive porphyritic basalt. Some hyaloclastites and Fe-Mn oxide crusts.
Amph D2	10°38'S 109°36'W	Sea mount	1790-2130 m	Iron hydroxide deposits. Some Mn oxide pebbles. A fragment of porphyritic basalt. Small chips of basaltic glass.
Amph D3	12°52'S 110°58'W	Undulating	2900-3000 m	Massive microcrystalline basalt with glass skin.
Amph D4	18°24'S 113°19'W	Undulating	2600-2700 m	Massive microcrystalline basalt with glass skin.
Amph D5	18°35'S 126°24'W	Sea mount	2600-3500 m	Hyaloclastites of various types, associated with Mn oxides. Some small fragments of porphyritic basalt.
Chall 276	13°28'S 149°30'W	Unknown	4300 m.	Small fragments of porphyritic basalt. Hyaloclastites associated with Mn oxides.

\* For details see text.

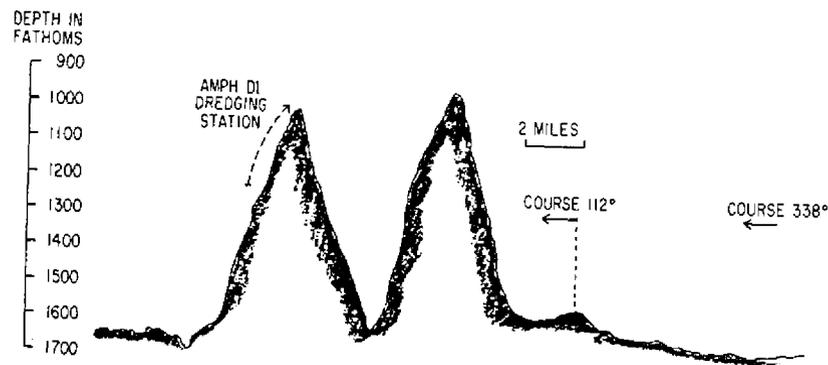


Fig. 2. P.D.R. profile of the bottom in the vicinity of station Amph D1. Vertical exaggeration is about 12 times.

TABLE 2. Wet Chemical Analyses of Deep-sea Basalts Dredged during the Cruise "Amphitrite" from the South Pacific\*

	D1a	D1b	D2	D3	D4	D5
SiO <sub>2</sub>	48.53	48.10	46.95	49.80	49.64	48.71
TiO <sub>2</sub>	0.76	1.25	1.35	2.02	1.37	2.10
Al <sub>2</sub> O <sub>3</sub>	22.30	16.44	16.48	14.88	16.19	15.68
Fe <sub>2</sub> O <sub>3</sub>	0.69	3.89	7.14	1.55	1.35	8.40
FeO	4.82	3.86	2.96	10.24	7.85	2.12
MnO	0.16	0.12	0.14	0.21	0.18	0.14
MgO	7.14	9.07	7.86	6.74	8.37	7.01
CaO	12.86	11.57	12.41	10.72	12.01	12.21
Na <sub>2</sub> O	2.18	3.40	3.29	2.91	2.75	3.02
K <sub>2</sub> O	0.06	0.20	0.25	0.24	0.11	0.24
P <sub>2</sub> O <sub>5</sub>	0.07	0.15	0.18	0.28	0.09	0.02
H <sub>2</sub> O <sup>+</sup>	0.38	1.89	0.83	0.54	0.50	0.50
H <sub>2</sub> O <sup>-</sup>	0.01	...	...	0.06	0.01	0.15
Total	99.96	99.94	99.84	100.19	100.22	100.30

\* Analyses of D1a, D3, and D4 are from Engel and Engel (1964). Analyses of D1b, D2, and D5 were made by R. Mazzuoli, Department of Petrology, University of Pisa, Italy.

displaying hyalopilitic textures. A chemical analysis by Engel and Engel (1964), reported in table 2, column D1a, characterizes this rock as a tholeiitic basalt.

When the original surface of the flows is present on the samples, it appears to be covered by an irregular, rough alteration crust of variable thickness (usually less than 1 cm), consisting of ferruginous and claylike substances, and of pockets of black, powdery Mn oxides. A chemical analysis of the latter is given in table 3, column a. Sections of several boulders show, within a crust of altered palagonitic material, a layer of fresh glass and a crystalline core (figure 3).

2. Some basaltic fragments were recovered that contain according to microscopic study, plagioclase plates together with abundant, fresh olivine and subordinate augite, the whole arranged in subophitic texture. Their chemical composition is in table 2, column D1b.

3. Some pebbles were recovered that consist of angular fragments of basaltic glass varying from a few microns to 1 or 2 millimeters in size and cemented together in some instances by black Mn oxides (figure 4b), in others by a ferruginous fine matrix (figure 4a). Such specimens show the

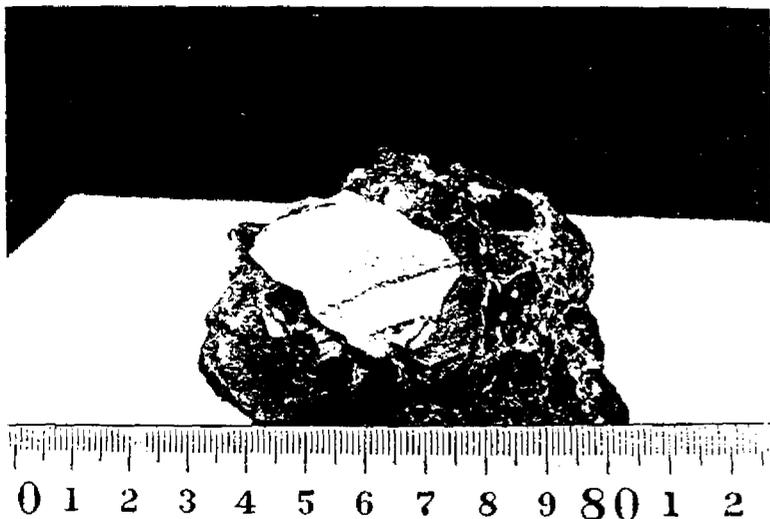


Fig. 3. Cross section of a specimen from dredge haul Amph D1. The light portion is the crystalline core within glassy phases.

TABLE 3. X-ray and Optical Spectrographic Analyses of Samples from Dredge Haul Amph D1\*

Per cent	<sup>Bd 54</sup> a	<sup>Bd 54</sup> b	<sup>© Bd 54</sup> c
SiO <sub>2</sub>	25.8	38.8	40.0
Al <sub>2</sub> O	6.5	11.6	10.2
CaO	6.35	11.6	10.1
MgO	5.0	7.0	10.0
K <sub>2</sub> O	0.65	0.43	0.16
TiO <sub>2</sub>	1.47	1.2	1.0
Fe	13.0	11.7	5.7
Mn	5.59	1.86	7.12
Fe/Mn	2.3	6.3	0.8

\* Analyses by O. Joensuu. For techniques and accuracy see O'Neil et al. (1960) and Rose et al. (1963). a = Fe-Mn oxides on the surface of basalt fragment of figure 3; b = hyaloclastic rock with ferruginous matrix (figure 4a); c = hyaloclastic with black manganese matrix (figure 4b).

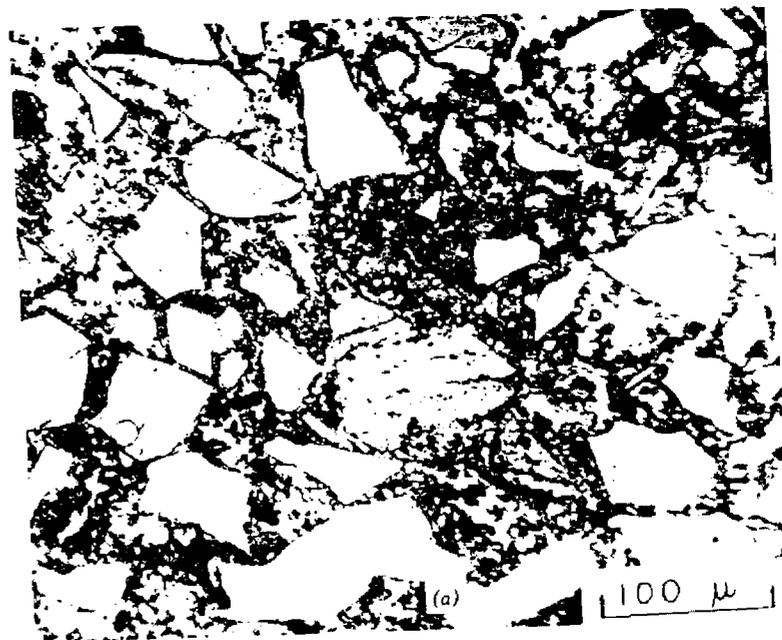


Fig. 4. Microphotographs of thin sections of two hyaloclastic rocks from dredge haul Amph D1. Transmitted light. (a) indicates basaltic glass fragments in ferruginous matrix. (b) indicates basaltic glass fragments in black, Mn oxide matrix.

petrological features characteristic of hyaloclastites.<sup>1</sup> Chemical analysis of two samples (table 3) confirm that the matrix of the hyaloclastite is in one case enriched with Fe, in the other enriched with Mn. X-ray diffraction study indicates that the ferruginous matrix is amorphous; it consists probably of palagonite and cryptocrystalline goethite. A few broken tests of *Foraminifera* and *Radiolaria* are also present in the matrix.

### Station Amph D2

A sea mount rises at this location near the crest of the East Pacific Rise, from a softly rolling bottom at about 3000 meters, up to at least 1790 meters below sea level. Dredging was done on the flank of the mount between 2130 and 1790 meters, and the following was recovered:

1. More than 80 per cent of the dredge haul consists of pebbles of a reddish, friable, powdery rock. X-ray diffraction study of the red material shows it is made of poorly crystalline  $\alpha\text{FeO}(\text{OH})$  (goethite). Chemical analyses are given in table 4, columns  $a_1$ ,  $a_2$ , and  $a_3$ , and show the material to contain around 30 per cent iron (Bonatti and Joensuu, 1966).

TABLE 4. Spectrochemical Analyses of Rocks from Dredge Haul Amph D2: \*  $a_1$ - $a_3$  = three different fragments of the red ferruginous rock; b = black, porous Mn oxide rock; c = black Mn oxide crust on basalt (d); d = olivine basalt fragment

	$a_1$	$a_2$	$a_3$	b	c	d
SiO <sub>2</sub> %	17.6	13.9	12.4	8.1	12.4	49.7
Al <sub>2</sub> O <sub>3</sub> %	1.0	<1	1.0	0.4	3.1	15.8
CaO %	2.6	2.3	2.7	2.5	5.2	12.3
MgO %	1.5	0.85	0.80	5.9	0.40	9.0
K <sub>2</sub> O %	0.39	0.45	0.38	1.29	3.8	0.16
Fe %	32.5	28.8	31.1	5.5	17.8	7.7
Mn %	1.94	2.43	0.58	38.72	19.67	0.18
Ni ppm	400	460	90	4500	3200	83
Co ppm	35	120	32	290	6800	63
Cr ppm	26	20	20	210	87	290
Fe/Mn	16.7	11.8	51.9	0.14	0.9	42.7

\* After Bonatti and Joensuu, 1966.

<sup>1</sup> The term "hyaloclastite," introduced by Rittmann (1961), indicates thermally shattered lavas produced during the interaction of hot lava with water. The term "aquagene tuff" has been used in the same sense by Carlisle (1963).

2. A fragment of relatively fresh basalt also was recovered, whose surface is partially encrusted by a thin (half a millimeter) layer of Mn oxides. Study of a thin section shows the presence of labradorite and olivine crystals in a ground mass of tiny plagioclase laths, serpentine-iddingsite, magnetite, and some glass. Several small fragments of basaltic glass were also recovered. The chemical composition of the basalt is given in table 2, column D2. Composition of the manganese crust is given in table 4, column c.

3. The dredge haul also included a few pebbles of black, earthy Mn oxides. Their chemical composition is given in table 4, column b.

### Station Amph D3

The ocean bottom at this location is mildly undulating, with reliefs of the order of some hundreds of meters (figure 5). The acoustic reflection in the P.D.R. record show a characteristic "reverberation effect" of the sound on the bottom (figure 6) due to scattering from small-scale relief and bottom irregularities of the order of few meters or less, and to a high acoustic reflectivity of the material exposed on the sea floor. This effect implies that hard rocks are exposed on the bottom that have not been covered by a thick sediment carpet, which would, if present, smooth away small-scale irregularities. Acoustic reflections indicating "reverberation" were present almost continuously in the P.D.R. record from about 40 miles before to 60 miles beyond the station point along the course of the ship, as shown schematically by figure 5.

A few hundred kilograms of rock were recovered from a dredge haul, consisting of fragments and boulders of a microcrystalline basalt. The boulders are of different sizes and shapes, but they frequently suggest pillow structures. Many of the fragments have in one of their surfaces, or occasionally in two opposite parallel surfaces, a crust about 0.1 to



Fig. 5. P.D.R. profile of the bottom in the vicinity of station Amph D3. The "reverberation effect" on the P.D.R. record is indicated. Vertical exaggeration is about 30 times. Vertical dashed lines limit a portion of the P.D.R. record showing reverberation and corresponding to about 30 miles, which was not included in the drawing.

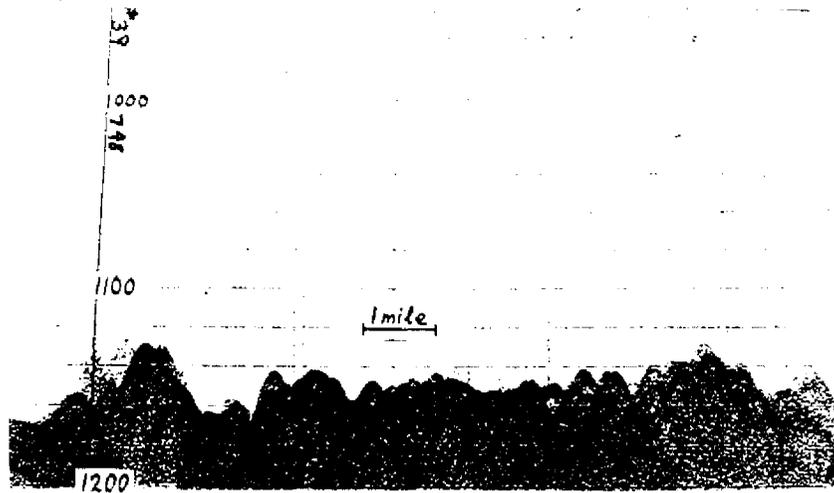


Fig. 6. Photograph of the P.D.R. record near station Amph D3 showing the "reverberation effect."

0.5 cm thick of a dark, fresh-looking glass, whose index of refraction is 1.60. The external surface of this glass is generally very smooth, but occasionally presents ropy structures of the type shown in figure 7. Between the glassy surface and the crystalline interior one can generally notice the presence of a great number of vesicles, ellipsoidal or spherical in shape, with diameters reaching up to one to a few centimeters, but usually of a few millimeters. In some instances it appears as if almost continuous empty chambers are present between the glassy crust and the crystalline interior. Thin-section study of the crystalline material shows very fine-grained minerals arranged in subophitic texture. Elongated plates of labradorite are present in a mass of serpentine-iddingsite and magnetite. Chemical analysis of a sample from this dredge haul is reported by Engel and Engel (1964) (see table 2, column D3).

#### Station Amph D4

The P.D.R. record near Station Amph D4 shows a softly undulating bottom between depths of 2900 and 3100 meters, with some "reverberation" similar to that observed at station Amph D3. A gentle hill rises to within approximately 2600 meters of the surface and gives a strong "reverberation effect" on the P.D.R. record. This hill was dredged and the material recovered was found to consist of abundant fragments of

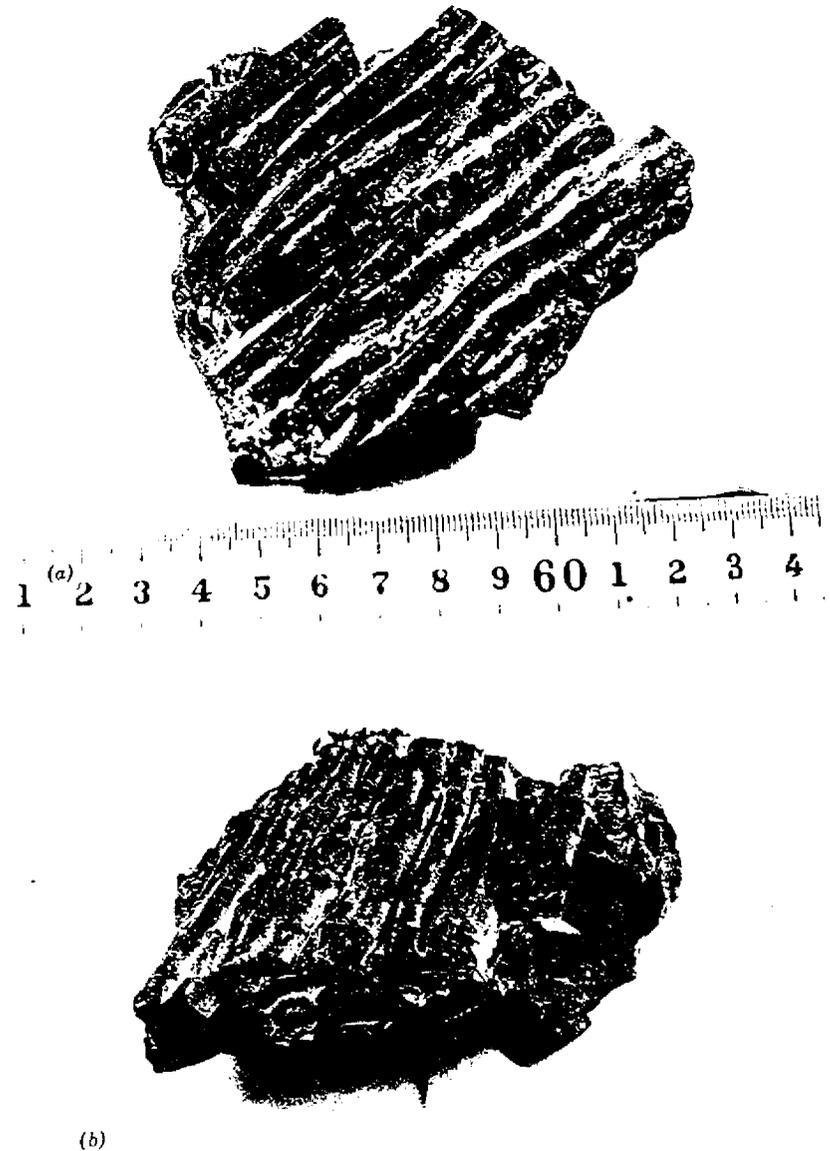


Fig. 7. Photographs of the ropy glass surface in a specimen from dredge haul Amph D3.



Fig. 8. Deep-sea photograph at station Amph D4 (photo by F. Dixon).

fresh microcrystalline and glassy basalt very similar to that found at Amph D3. A crust of fresh glass up to a few millimeters thick covers the surface of the boulders, which, often concave, suggest pillow shapes. The microcrystalline basalt beneath the glassy crust consists of tiny laths of labradorite, associated with remnants of olivine, and secondary products, such as serpentine and magnetite. The results of a chemical analysis (from Engel and Engel, 1964) are given in table 2, column D4. A photograph of the bottom at this location is presented in figure 8.

#### Station Amph D5

The bottom topography of an area of about 100 square miles of the south Pacific was surveyed in some detail. A buoy with a radar-reflecting screen was anchored at 18° 35' S, 126° 30' W, and a network of crossings was established with the ship around the buoy. The position of the ship was determined, relative to the buoy, up to a distance of 10–12 miles by the radar at time intervals of approximately 1–2 minutes each. In correlation with these readings the bottom depth was also read at the P.D.R. In this way the bathymetric map of figure 9 was constructed.

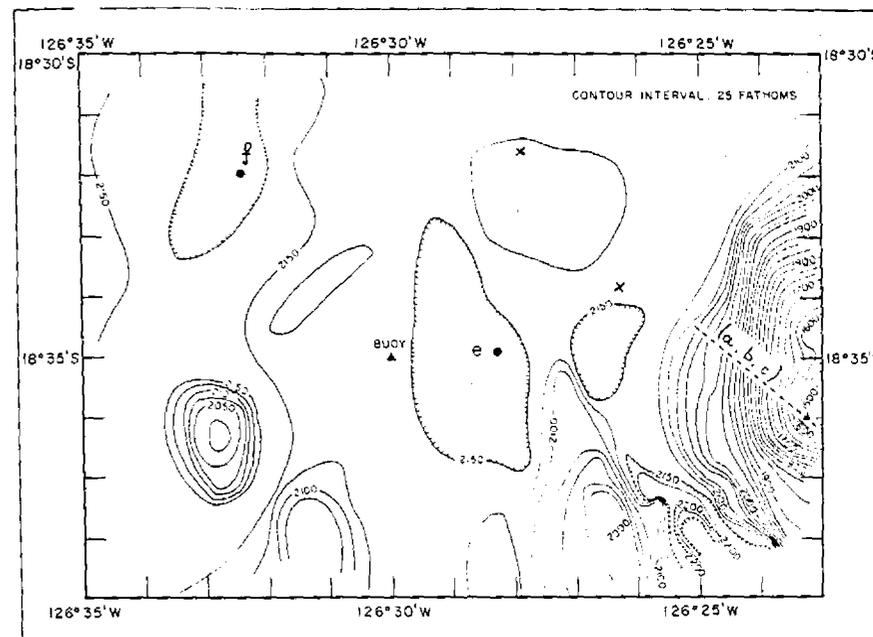


Fig. 9. Bottom topography of survey area Amph D5. Dashed line indicates the location of the Amph D5 dredge and camera stations. (e) and (f) are the location of sediment cores. Crosses indicate locations where coring attempts were unsuccessful because of hard bottom.

A portion of a sea mount with a relief of approximately 1250 meters was included in the area surveyed. The western side of this sea mount was dredged and photographed (some of the photos are shown in figures 10, 11, and 12). Some sediment cores were also taken in a flat area immediately west of the sea mount at sites shown in figure 9. The material recovered from dredging the side of the sea mount consists of the following.

1. A few small pebbles of basalt were recovered. Thin-section study shows the rock has a porphyritic structure with phenocrysts of fresh labradorite, in a ground mass of fine laths of labradorite, altered olivine (serpentine and iddingsite), and magnetite. The results of a chemical analysis of this basalt are given in table 2, column D5.
2. Coarse hyaloclastic rock was recovered, with a typical breccia-like appearance and consisting of fragments of dark basaltic glass up to a few millimeters in diameter, encrusted and cemented by a yellowish

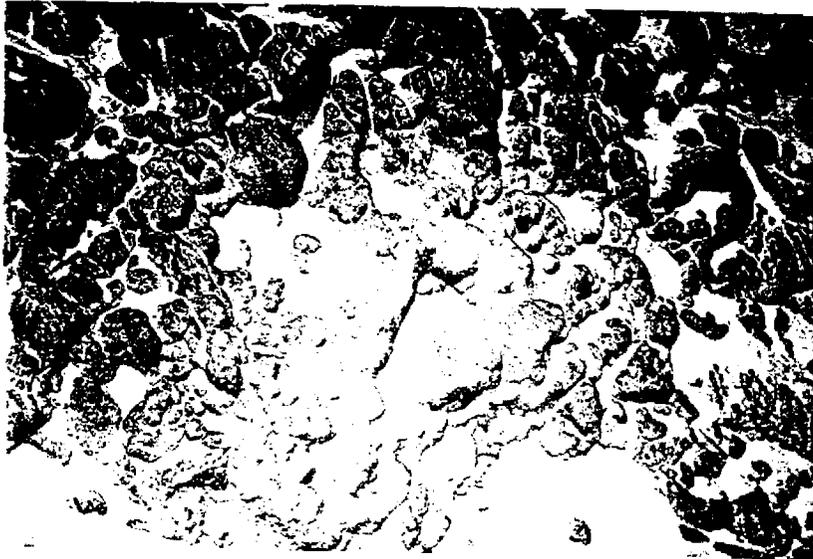


Fig. 10. Deep-sea photograph of the flanks of sea mount Amph D5 (photo by F. Dixon).



Fig. 12. Deep sea photograph of the flanks of sea mount Amph D5 (photo by F. Dixon).

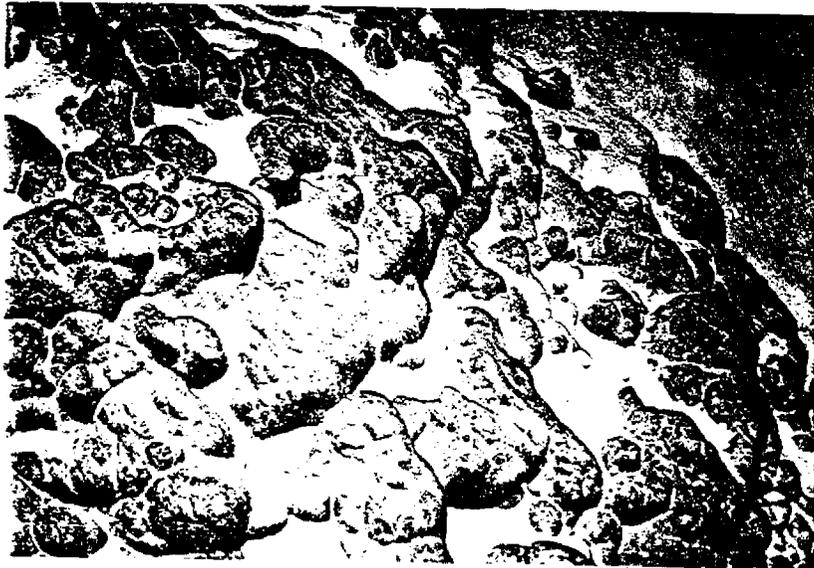


Fig. 11. Deep-sea photograph of the flanks of sea mount Amph D5 (photo by F. Dixon).

powdery matrix (figure 13a and b). From thin sections, grains of yellowish palagonite of various sizes are recognizable; the larger have a core of unaltered basaltic glass (sideromelane) (figures 14 and 15). Inclusions of fresh feldspars and olivine were observed occasionally in the glass. Darker concentric rims appear in the yellow-brown palagonitic material. This same type of material constitutes the matrix among the grains, together with some sediment and a few broken tests of foraminifera. X-ray powder diffraction analyses of the palagonitic material reveals the presence of expandable 15 Å clays of the smectite family, probably nontronite, as the main crystalline phase.

3. The bulk of the haul was made up of pebbles of various sizes of a friable, fine-grained light-gray material. The density of this rock, measured with a pycnometer, is 2.0. Dark concentrations of Mn oxides are observed on the surface (table 5) and dispersed in the interior of these specimens, resulting in their spotty appearance (figure 16). Thin sections were prepared after this material was impregnated with epoxy resins. The bulk of the rock is made up of partially altered palagonitic grains, similar to those described above, but of smaller size; some crystals of fresh labradorite are included within the rock (figure 17a and b). Opaque segregations of manganese oxides are abundant in the section.

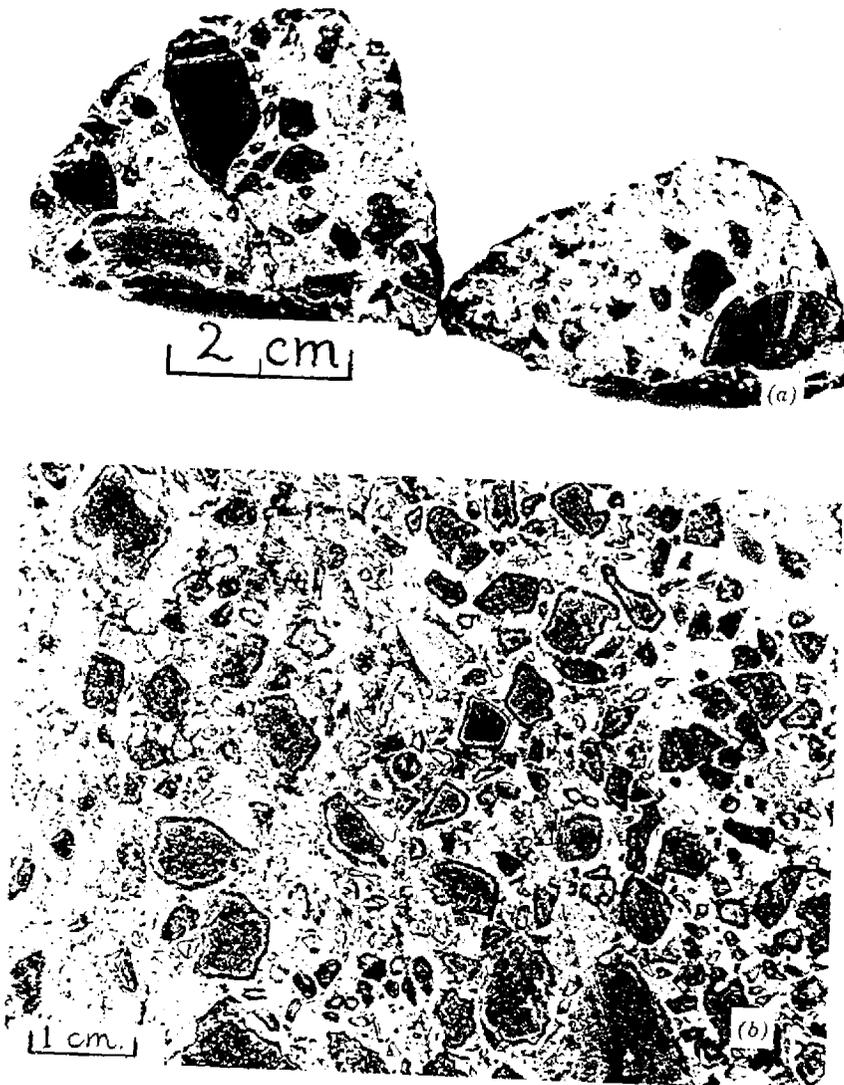


Fig. 13. Photographs of cross sections of coarse hyaloclastic rocks from dredge haul Amph D5.

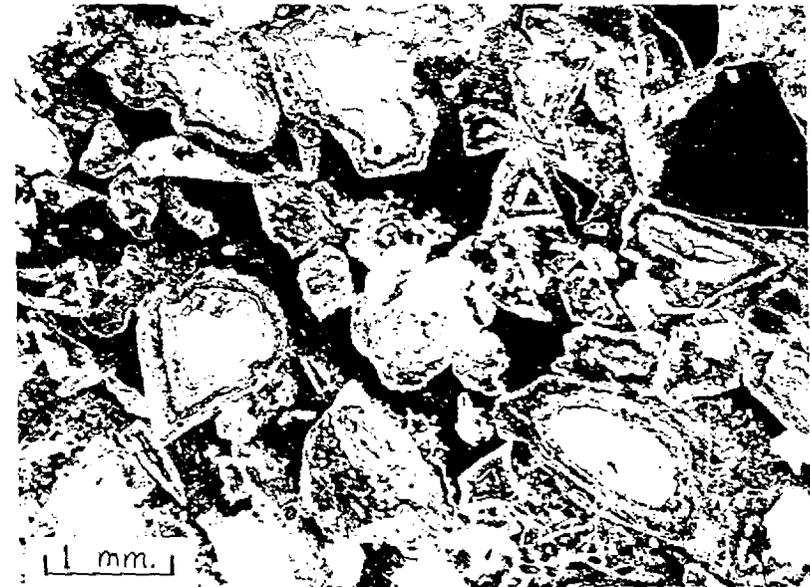


Fig. 14. Thin section of a coarse hyaloclastic rock from Amph D5. Transmitted light. Note the larger grains with a core of fresh basaltic glass and a rim of concentric-layered, reddish-brown palagonitic material.

By x-ray powder diffraction, smectites were revealed to be the most abundant crystalline phase, together with very small amounts of phillipsite; in addition the presence of plagioclase was confirmed. Chemical analyses of this rock were performed, before and after dissolving the Mn oxides, by treating the sample with a 1 *M* solution of hydroxylamine. [Such treatment dissolves quantitatively Mn oxides but leaves silicates unaffected (Arrhenius, Bonatti and Kharkar, in preparation).] The results of the analyses are given in table 6.

At several spots in the nearly flat area west of the sea mount (figure 9) attempts were made to collect bottom cores. At two localities no core was recovered because of hard bottom, while at two other sites the following sediment samples were collected:

1. At station Amph 39, a dark chocolate sediment was recovered. Under the microscope the material appears to be fine grained (the majority of the particles are  $<50 \mu$  in size). Altered hyaloclastic grains, crystals of phillipsite, and opaque ferromanganese oxide particles could be recognized; x-ray powder diffraction study of the material showed that phillipsite and expandable phyllosilicates (smectites) are the most



Fig. 15. Thin section of a hyaloclastic grain, showing a core of fresh basaltic glass and a rim of reddish-brown palagonitic material. From coarse hyaloclastite Amph D5. Transmitted light.

abundant crystalline species. This sediment contains 45.6 per cent  $\text{CaCO}_3$ , mainly in the form of single crystals of calcite up to  $60 \mu$  in size.

2. At station Amph 40, a dark chocolate sediment was also found, with the same character and composition as Amph 39, except for the absence of single crystals of calcite. The  $\text{CaCO}_3$  content is only 9.5 per cent, in the form of Foraminifera tests.

TABLE 5. Chemical Data on Black Mn-Fe Oxide Crust on Fine Hyaloclastite Rock of Fig. 16\*

$\text{SiO}_2$ %	14.9
$\text{Al}_2\text{O}_3$ %	4.6
Fe %	19.1
Mn %	19.2
Ni ppm	8800
Co ppm	3900
Cr ppm	36
Cu ppm	1200

\* After Bonatti, 1966a; analyses by O. Joensuu. For techniques and accuracy see caption of Table 3.

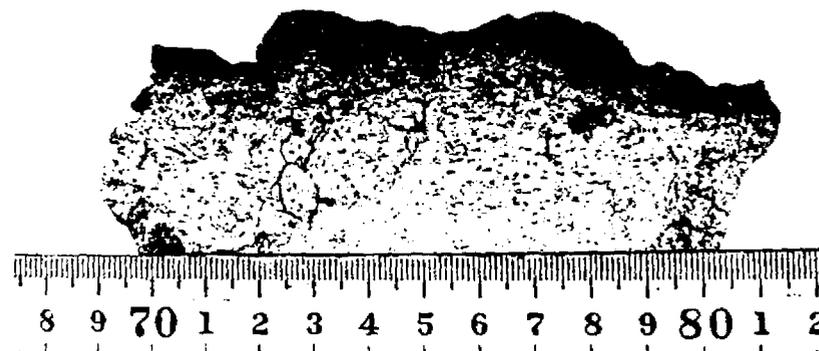


Fig. 16. Sectioned hand specimen of fine hyaloclastic rock Amph D5. Black spots within the rock are due to fine manganese oxide aggregates.

#### Station Challenger 276

During the Challenger Expedition (1872-1876), rock fragments, Mn nodules, and fine sediments were recovered at station 276. The remarkable features of this material warranted a restudy of part of it; the results are reported here together with some of the original data of Murray and Renard (1891).

Solid fragments up to a few millimeters in diameter are quite abundant; thin-section study shows these coarser grains to consist of the following.

1. Fragments of glassy basalts, consisting of laths of plagioclase within the labradorite-bytownite range and of strongly altered (iddingsite) pyroxenes and olivine in a matrix of dark glass with ferruginous inclusions (tachylite).
2. Grains of basaltic glass with zones consisting of radiating acicular crystals optically identified as natrolite. Ferruginous (goethite?) segregations are abundant mainly at the edges of the grains.
3. The majority of the grains recovered are of palagonite, from which well-formed crystals of phillipsite are developed (figure 18a and b). The larger grains have cores of fresh basaltic glass (sideromelane). Associated with such grains as crusts and fillings are dark ferromanganese oxides. Some of the grains show a nucleus of crystalline basalt, which grades into a clear glass (sideromelane) towards the edges and further into a crust of altered palagonitic substance.

The coarser material just mentioned ranges down in size to a fine sediment of "red clay" type, which was studied by x-ray powder diffraction

TABLE 6. Chemical Data on Samples from Dredge Haul Amph D5:\*

a = microcrystalline basalt; b<sub>1</sub> = fine hyaloclastite; b<sub>2</sub> = fine hyaloclastite (b<sub>1</sub>) after treatment with hydroxylamine. Such treatment dissolves quantitatively manganese oxides, leaving silicates unaffected (Arrhenius et al., in preparation)

	a	b <sub>1</sub>	b <sub>2</sub>
SiO <sub>2</sub> %	46.5	53.0	51.2
Al <sub>2</sub> O <sub>3</sub> %	14.2	14.7	14.8
Fe%	6.79	9.1	9.7
Mn%	0.29	1.23	0.034
Ni ppm	70	1000	41
Co ppm	75	46	<10
Cr ppm	230	49	83

\* After Bonatti, 1966a; analyses by O. Joensuu.

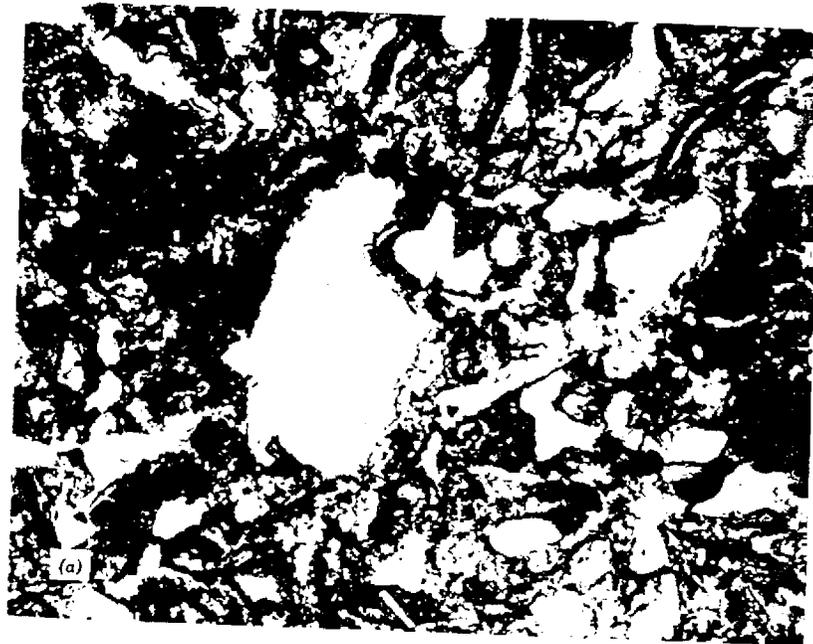


Fig. 17. Thin sections of labradorite crystal in fine-grained hyaloclastic rock from Amph D5. (a) indicates the view with transmitted light, parallel nicols. (b) indicates the view with crossed nicols.

and optical means. This sediment was found to have a carbonate content of 39.9 per cent as determined by a volumetric method.

The main crystalline component of this fine red clay is phillipsite, which under the microscope appears in the form of prismatic crystals often associated with small palagonitic grains in a manner similar to that described elsewhere (Bonatti, 1963). Some feldspar grains and tiny Mn and Fe oxide particles also were observed. Clay minerals of the montmorillonite group were detected by x-ray diffraction. The remarkable carbonate fraction consists of single crystal grains of calcite up to 50–60  $\mu$  in size and of irregular shape and of well-formed rhombs of dolomite of similar dimensions. Such carbonates have been described in detail by Bonatti (1966).

More than half a ton of manganese nodules between 1 and a few centimeters in diameter were recovered by the "Challenger" at station 276. Iron and manganese oxides are associated in these nodules with altered hyaloclastic material, as observed by the present author and as documented in their description by Murray and Renard (1891). According to Riley and Sinhasemi (1958) the crust of one such nodule contains 29.1 per cent Mn and 26.1 per cent Fe.

That this region of the Pacific is generally affected by extensive recent volcanism is indicated by the finding of anomalous specific alkalinity, salinity, and oxygen content of deep water at the Swedish Deep Sea Expedition Station 105, located a few hundred miles north of Chall 276 (Koczy, 1956). Local injection of "volatiles" from the sea floor into the bottom water was suggested by Koczy (*ibid.*) to explain



Fig. 18. Thin sections of phillipsite crystals developing from hyaloclastic grains at Chall 276 station. Transmitted light.

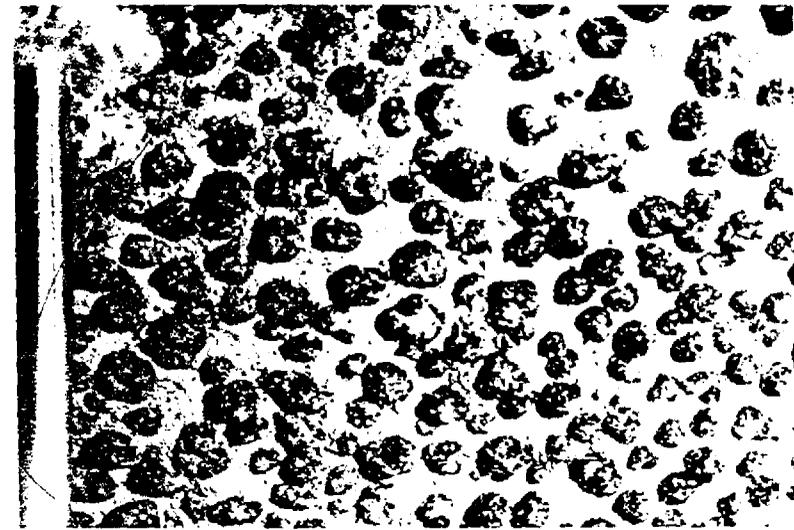


Fig. 19. Deep-sea photograph of manganese nodules in an area close to Chall 276 station (photo by S. Calvert).

such anomalies. Subsequent expeditions have discovered widespread deposits of Fe-Mn oxides close to Chall 276 location. A bottom photograph taken by S. Calvert at  $13^{\circ} 53' S$ ,  $150^{\circ} 35' W$  is shown in figure 19. Mero (1965, p. 161) states that "Dredging, coring, and photography in this area of the ocean indicate a deposit of nodules covering at least several thousand square km."

#### Discussion

The submarine lavas described in the previous section may be divided into two distinct types.

One type (exemplified by Amph D3 and Amph D4) consists wholly of compact crystalline and glassy phases petrologically similar to subaerial products.

Lavas of the other type (exemplified by Amph D5, Chall 276, and, to a lesser extent, by Amph D2 and Amph D1) share the following common characteristics.

1. Large amounts of the lava appear to have been granulated or pulverized.
2. Extensive amounts of hydrated glass (palagonite) and of secondary minerals such as smectites and zeolites are present.

3. The products are often intimately associated with deposits of ferro-manganese oxides.

These features are certainly not common in subaereal volcanics and were not found in the submarine lavas of the first type.

It will be assumed for the moment that these two types of volcanic products are the result of two distinct lava-sea water interactions; in the former type, interaction between hot lava and sea water during the eruption is negligible, while in the latter type it is very strong. For the sake of clarity I will call the former type of effusion "quiet," the latter, "hyaloclastic."

### Quiet effusion

The rocks from Amph D3 and Amph D4 seem clearly to have formed in quiet eruptions of lava, without much interaction with sea water. As soon as the lava came into contact with water and/or wet sediment, a thin layer of melt was chilled instantly, forming a crust of glass which acted as a thermal insulator under which the fluid basalt could circulate and cool, thus gradually giving rise to a more-or-less crystalline, fine-grained rock. The lack of first generation phenocrysts in rocks D3 and D4 indicates that the lava was wholly liquid when it erupted on the ocean floor. The smooth concave glassy surface of many of the boulders recovered in those dredge hauls suggest that pillow lavas are common among these basalts. The origin of such structures probably took place in the manner suggested by Rittmann (1961): when the fluid hot melt, accumulating within glassy insulating surfaces, finds resistance toward its lateral expansion, it tends to deform the still-plastic crust, giving rise to spherically shaped, pillow-like boulders. Such mechanism has been directly observed in lavas flowing under shallow water (Anderson, 1910). The ropy structure of the glassy crust in several samples from Amph D3 (figure 7) may be ascribed to the shearing action of the underlying flowing hot melt on the still-plastic crust. Generally speaking these lavas are somewhat similar to subaerial "pahoehoe" types.

Under favorable conditions submarine lavas produced by quiet effusion may be able to flow for considerable distances both as sills between the upper strata of the sedimentary column or on the surface of the sediment. It was mentioned earlier that many of the basaltic boulders recovered at station Amph D3 show a great number of vesicles between the glassy crust and the underlying microcrystalline rock, so that in some cases an almost continuous gas layer exists between the two phases. The same characteristics were described by MacDonald (1953) for Hawaiian

lavas, where the glassy skin "commonly confines just below it a layer of gas bubbles risen from the underlying fluid." The presence of a thin fluid layer between the rapidly formed viscous glass and the hot melt would decrease the resistance to the flow of the latter. It was reported, describing dredge haul Amph D3, that the area covered by the flows is rather extensive and looks like a mildly undulating, low plateau (figure 5); it seems likely that this basalt derives from one or many fissure-type effusions.

Basalts, similar to the type described above, have been recovered from the deep sea in other places. Thus Moore and Reed (1963) and Moore (1965) described pillow basalts dredged from the submarine part of the east rift zone of the Kilauea Volcano, off the island of Hawaii. These basalts have, according to Moore (*ibid.*) a thin, smooth crust of fresh glass and generally show features very similar to those of Amph D3 and Amph D4, indicating little or no interaction with sea water during their emplacement. It is indeed remarkable that the type of volcanic products described in this section seem to be prevalently associated with hilly or undulating bottom topography rather than with such major features as sea mounts or guyots.

### Hyaloclastic eruption

I shall briefly discuss some of the above-mentioned characteristic features of rocks Amph D5, Chall 276, etc., and test the assumption that such features were produced by a particular type of submarine eruption, rather than by post-eruptive, slow, gradual alteration of massive basalt.

**Fragmentation of the lava.** An agent capable of mechanically fragmenting (figures 4 and 13) an originally compact basalt is lacking in the deep sea.

The size distribution of the fragments (in the case of Amph D5 and Chall 276 they range from a few microns to a few centimeters in diameter) also is not typical of secondary action. Because secondary brecciation probably did not take place on the ocean floor, it has to be assumed that the fragmentation was primary, and originated during the eruption.

Granulation of a submarine lava into particles from a few microns to centimeters in size could be due to mechanisms similar to those causing formation of ash in subaerial volcanoes, that is, to explosive release of volatiles from the lava. Rittmann (1961) has pointed out, however, that at depths under the ocean where hydrostatic pressure exceeds the critical pressure of water, magmatic volatiles cannot be released in an explosive

fashion. McBirney (1963) has further discussed this problem and estimated that formation of ash could exceptionally take place at depths as great as 2000 meters below sea level but that the limit should normally be at a depth of around 500 meters for basaltic magmas.

In contrast, there is plenty of evidence that granulation and pulverization of the lava upon eruption takes place at any depth on the ocean floor and is not limited to shallow water. Examples of deep sea recoveries of breccia or tuff-like rocks include samples from Amph D5 (the depth of the summit of the sea mount is about 2700 meters), Chall 276 (depth 4300 meters), and Amph D1 (depth 1800 meters), in the present work. Rocks very similar to the coarse hyaloclastic breccia of Amph D5 were recovered from the south Pacific at Challenger station 285, at a depth 4300 meters (Murray and Renard, 1891, plate 18, figure 1) and at Challenger station 293, at a depth of 3650 meters (op. cit. plate 19, figure 3). Other examples are from a north Atlantic abyssal hill at 4960 meters (Matthews, 1961), from the McCall sea mount (at a depth of 1010 meters) near Hawaii (Moore, 1965), from a depth of 1260 meters on the Mendocino Ridge in the north Pacific (Bonatti and Nayudu, 1965), from the Seine sea mount (at a depth of 1000 meters) in the eastern Atlantic. In addition hyaloclastic grains are a major component of the south east Pacific pelagic deposits, most of them being found at depths greater than 2000 meters (Bonatti, 1963). It is very unlikely that these products were all erupted at or near the sea surface from volcanoes which subsequently sank to their present depth. A mechanism must exist which permits comminution of lavas also in the deep sea.

Explosive granulation of deep-sea lavas probably takes place when the hot melt and sea water come into contact; the principal factor is the sudden quenching of the former by the latter. If a fragment of lava at a temperature of the order of 1000° C is dropped into cold water, it would be suddenly chilled and its viscosity would increase very rapidly, more rapidly at the surface than in the core. Anisotropic stresses caused by differential contraction might give rise to explosive shattering of the fragment. Such a process was experimentally verified by Carlisle (1963), who also suggested that it was the cause of the extensive comminution of a submarine lava formation from British Columbia. The building up of deposits of hyaloclastites several hundred meters thick in the Ibleian Mountains (eastern Sicily) is also ascribed (Honnorez, 1961) to granulation of the lava when the first contact with sea water was made. Such explosive fragmentation has been also observed directly on several occasions; I limit myself to a quotation from an account of the recent submarine eruption which gave origin to the island of Surtsey, off Iceland (Thorarinsson, 1965, p. 54): “. . . from the very beginning of the lava

eruption it has been striking how much of the lava becomes fragmented when coming in contact with sea water. Explosive pseudoeruptions on a small scale could frequently be observed . . . .”

There is no reason to believe that the conditions prevailing at great depths below sea level limit in any way the efficiency of such thermal shattering and the consequent formation of hyaloclastites.

**Presence of palagonite.** The main component of the grains produced by the above-described fragmentation of the lava is palagonite. Palagonite consists essentially of hydrated glass together with its alteration products, usually smectitic clays. It has been found in several localities on land, always in connection with lavas thought to have been erupted under water or ice. In some cases, such as in Iceland (Peacock, 1926), palagonite constitutes a matrix which encloses fragments of normal basaltic glass and occasionally also crystalline basalt fragments. In other cases palagonitic grains up to a few millimeters in diameter make up the main body of thick formations, such as in the submarine volcanics of eastern Sicily (Honnorez, 1961).

The most striking feature of palagonite is its high water content, which has been reported to reach more than 20 per cent in some cases (Peacock and Fuller, 1928), in contrast with most volcanic glasses, which contain at most 2 or 3 per cent water. Such an elevated water content of palagonite cannot in many deep sea occurrences be accounted for by gradual hydration at low temperatures of basaltic glass that originally was almost anhydrous. In fact, hydration of volcanic glasses in seawater and at low temperatures by diffusion of water molecules from the surface of the glasses inwards appears to be a very slow process, even relative to a geological time scale (Marshall, 1961). On this basis and on other geological grounds discussed in detail by Bonatti (1965) it is concluded that deep sea palagonite must be formed mainly at high temperatures directly by hydration of the lava during effusion under water.

To explain the presence of large quantities of palagonite in hyaloclastic volcanism, it has to be assumed that when the hot melt and seawater come into contact a portion of the fragmenting lava becomes hydrated at a rapid rate. The extent of this hydration depends on the temperature and possibly the pressure at which the contact between water and lava takes place, on the subsequent rate of cooling of the lava, and on the extent to which the lava is fragmented.

On the assumption that hydration operates mainly through diffusion of water molecules into the lava at the water-lava interfaces, the rate of hydration will increase exponentially with increasing temperature, according to the well known dependence of diffusion rates on temperature.

The rate of cooling of fragmented lava after effusion will generally be very rapid, due to the near-freezing temperature and high heat capacity of the bottom water; however, the hydration necessary to explain the observed quantities of palagonitic glass of these lavas could have taken place in such short times, if it is kept in mind that the lava comes in contact with sea water at temperatures near 1,000° C so that hydration rates should be very high (Bonatti, 1965).

Comparison of natural hyaloclastic grains with glasses artificially hydrated in the laboratory should clarify the means by which hydration takes place. Fragments of fresh basaltic glass (taken from the crust of Amph D3 rocks) were kept by A. McBirney (personal communication) in a hydrothermal bomb in water at various temperatures and pressures. After 10 hours at 350° C and under 125 bars pressure, hydration skins several microns thick were developed on the grains, similar to those on the coarse hyaloclastic rocks from Amph D5 described above (figure 14 and 15). The effect of water pressure on the hydration rate is not well known; McBirney's experiments seem, however, to indicate a strong increase of the rate of hydration of the glass with increasing pressures. Extrapolation of these results suggest that hydration effects observed in deep sea hyaloclastites could take place in time of the order of less than hours during cooling of the lava fragments, starting from temperatures close to 1000° C.

The hydration will also greatly depend on the extent to which the lava is comminuted during effusion, because fragmentation will increase the surface of contact between lava and sea water. The fragmentation of a cubic meter of lava into particles each 1 mm<sup>3</sup> in volume would increase the active surface by 10<sup>3</sup>, and the volume of lava which would suffer hydration would increase by a corresponding factor. Larger lava fragments (such as the one in figure 3) develop within the altered crust a portion of fresh glass derived from the quick chilling of the melt, while the slowly-cooled core gives rise to crystalline phases. The formation of extensive palagonite and the fragmented state of much of the products of hyaloclastic volcanism are closely related phenomena, both due to extensive interaction of hot lava and sea water during the submarine eruption.

X-ray powder diffraction patterns of palagonitic grains (such as hyaloclastites from Amph D5) often show the presence of silicates of the montmorillonite family. Smectites are produced on the sea floor by gradual alteration of hydrated basaltic glass, but they may partly be formed at the high-temperature during the lava-water interaction. The possibility of high-temperature formation of montmorillonite is well established (Hauser and Reynolds, 1939).

Review of past work on palagonites shows that crystals of feldspar that had crystallized before the basaltic melts were effused underwater appear generally not to be affected by the high-temperature lava-water reactions that produce palagonite. Such observations support the hypothesis that the reactions in question take place rapidly. Illustration of this is given again by Amph D5, where labradorite crystals embedded within the hyaloclastites are perfectly fresh (figure 17).

Although the above appears to be the general case, in a few instances evidence that the lava-water reactions also affected the feldspar grains has been obtained. Microscopic study of some basaltic rock fragments recovered from the Barracuda Fault Zone (western Atlantic), 3800 meters below sea level, shows altered glass that includes large euhedral crystals of labradorite, partially or totally replaced by a fine aggregate of radially arranged clusters and needles of zeolites of the natrolite group and by microcrystalline calcite (figure 20). The original outline of the plagioclase crystals is clearly recognizable even when replacement has been complete. The glassy groundmass is in part replaced by veins and fillings where analcite, calcite, natrolite, and possibly a zeolite of the

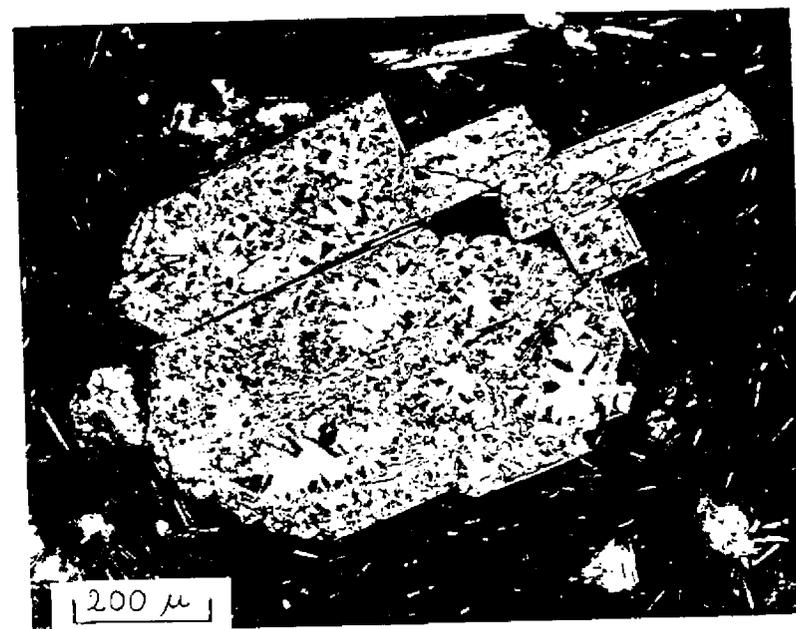


Fig. 20. Thin section of a crystal of labradorite completely replaced by aggregate of zeolites and calcite. Transmitted light. The rocks were recovered from the Barracuda Fault area (western Atlantic).



Fig. 21. Zeolites and calcite as a matrix of altered basaltic glass in rock samples from the Barracuda Fault area. Transmitted light.

phillipsite group are dominant (figure 21) in a mineral assemblage with typical "hydrothermal" character; in some fragments these alteration products almost completely replace the original material. Such mineral assemblage can form at low temperature in strongly alkaline solutions (Hay, 1966); however phillipsite and possibly clinoptilolite appear to be the only zeolites produced by the slow alteration at low temperatures of basaltic-palagonite grains in deep seawater of normal composition (Bonatti, 1963); therefore, the presence of a mixture of other zeolites, such as natrolite and analcite, as well as the alteration of the feldspars, probably indicates prolonged and extensive reactions at temperatures higher than those prevalent on the ocean floor. Laboratory synthesis of zeolite phases support such conclusions (Hawkins and Roy, 1963). The mineralogy of samples from station Chall 276 also indicates the lava fragments were held at high temperatures in seawater longer than generally was the case in hyaloclastic eruptions.

**Association with deposits of Fe and Mn oxides.** As has been reported in a previous section, rocks from stations Amph D2, Amph D5, Chall 276 and, to a lesser extent, Amph D1, were found to be closely

associated with concentrations of oxides of Fe and Mn, whereas Amph D3 and Amph D4 (i.e., those rocks produced in absence of strong water-hot lava interaction) showed no such feature. It is well known that oxides of Fe and Mn, which slowly precipitate from normal seawater, are frequently found to encrust hard rocks exposed on the sea floor; thus a possible explanation of the observation above would be that Amph D3 and Amph D4 basalts are younger than Amph D1, D2, D5, and Chall 276 and insufficient time was available for Fe-Mn oxides to encrust them. However, there is no evidence that D3 and D4 basalts are younger than D1, D2, D5, and Chall 276, because the alteration features presented by the latter rocks were shown above to be mainly produced in a relatively short time at high temperature during the submarine eruption.<sup>2</sup> The suspicion arises that local volcanic activity may have contributed substantially to the formation of the deposits in question and, further, that such a contribution may not have been made in the case of lavas extruded quietly (Amph D3 and D4); the deposits in question are related specifically to hyaloclastic eruptions.

In the case of Amph D5 it was found (see table 6) that the glassy hyaloclastic grains associated on the sea mount with Mn oxides contain about one order of magnitude less Mn than the fresh basalt which had erupted at the same location without directly reacting with seawater. Detailed discussion of these results will be found in Bonatti (1967). Moore (1965) similarly found that the Mn content of some hydrated basalts associated with Mn oxides from the McCall sea mount (off Hawaii), is about one half that of fresh basalts from the same location, and stated: ". . . perhaps alteration liberated MnO which was then free to redeposit as encrustations on the surfaces of the basalt."

The results given above support the hypothesis that Mn and other ferrides may be leached out of submarine lavas during their interaction with seawater. This hypothesis was proposed by Krauskopf (1956, 1957) to explain a number of Mn deposits from various emerged regions associated with basalts of submarine origin. In fact, the association of submarine basalts, red cherts, and Fe-Mn ores was recognized as characteristic of ancient geosynclines (Alps, Appennines, etc.) in the last century by Steinmann. This same hypothesis was applied by Bonatti and Nayudu (1965) to explain the formation of several deep sea Fe-Mn oxide deposits closely associated with hyaloclastites in the Pacific.

The leaching of Mn and ferrides from lavas, which probably takes place at high temperature, is favored by the presence of acidic magmatic gases dissolved in seawater during the eruption, and should be greatly

<sup>2</sup> Some preliminary K/Ar tests suggest that basalts Amph D1 and D3 have a similar age, of the order of one or few million years. (J. Dymond, personal communication.)

dependent on the extent to which the lava is comminuted. Lavas, which are not granulated during the eruption, that is, lavas erupted "quietly," should suffer little or no chemical leaching of this type, thus explaining the scarcity of the Fe-Mn deposits associated with them.

The rate of oxidation of the solutions enriched with Fe-Mn is determined by the availability of oxygen. Boström (1967) estimated that about 4000 liters of seawater are necessary to oxidize one mole of  $Mn^{2+}$  into  $Mn^{4+}$ , assuming the water contains  $10^{-4}$  mole/liter of dissolved oxygen. It has to be considered that during the volcanic activity the presence of a localized heat source on the sea bottom should give rise to thermal instability of the deep water masses, resulting in convection currents and in a continuous and a relatively rapid supply of new oxygenated water to the eruption site. Thus, of the elements put in solution, most of the iron should quickly precipitate, giving rise to localized iron hydroxide deposits, such as the one discovered on the Amph D2 sea mount. Manganese is likely to remain for a longer time in solution; it is gradually oxidized and precipitated both near the eruption site and on areas adjacent to it. As a result, oxide and hydroxide rocks recovered from an eruption site of this type have diverse Fe/Mn ratios, as is illustrated by the set of samples from station Amph D2 (table 4).

Among the minor elements, Ni, Co, and Cr appear also to be leached to some extent during hyaloclastic eruptions (table 6). Ni follows Mn rather than Fe during precipitation (figure 22), whereas Cr does not precipitate upon oxidation and is probably maintained in solution as  $(CrO_4)^{-2}$  (Arrhenius and Bonatti, 1965). The concentration and distribution of Ni and Co in deep oceanic water masses confirms the importance of submarine volcanism as one of their sources in the south Pacific (Schutz and Turekian, 1965).

Two other processes may contribute to the peculiar chemistry of deposits connected with deep-sea volcanism in the Pacific:

1. Direct introduction of various elements into bottom seawater by hydrothermal activity (Wedepohl, 1960).
2. Mobilization and redistribution of some components of pelagic sediments (such as the ferrides) due to warm solutions related to volcanism (Lynn and Bonatti, 1965; Boström, 1967).

The over-all distribution of the ferride elements in pelagic sediments of the south Pacific is strongly influenced by the aforementioned processes which superimpose their effect upon that which is due to the continuous, slow deposition of terrigenous ferrides; note, for instance, the high concentration of iron and manganese on the East Pacific Rise (Skornyakova,

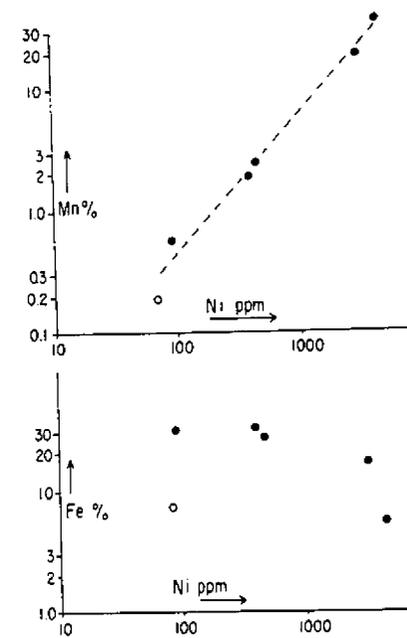


Fig. 22. Mn/Ni and Fe/Ni relations in samples from dredge haul Amph D2. The open circles indicate the basalt fragment. Full circles indicate the oxide and hydroxides of table 4.

1965). Several other elements are probably also affected, as discussed in detail by Boström (*loc. cit.*).

**Areal influence of hyaloclastic volcanism.** Contrary to the case of "quiet" effusions, there is ample evidence that "hyaloclastic" volcanism extensively affects the mineralogy and chemistry of bottom deposits in wide areas adjacent to the site of the outbreak. Hyaloclastic debris produced by the volcano are set in suspension in the bottom water by their explosive shattering. Turbulence and convection currents created by the presence of a local heat source, as well as normal bottom currents, and possibly also turbidity currents from the slopes of the sea mount, scatter the finest debris in areas adjacent to the eruption, probably contributing to the formation of Menard's (1964) "archipelagon aprons" around sea mounts. After settling on the ocean floor, hyaloclastic grains will slowly react with seawater to form more stable phases such as minerals of the montmorillonite family and zeolites, mainly phillipsite (Bonatti, 1963, 1965; Arrhenius, 1963; Peterson and Griffin, 1964). These silicates are

the major phases of deposits close to sites of hyaloclastic volcanism, provided they are not diluted by terrigenous and/or biogenous components. It has to be pointed out that the rate of alteration of hydrated glass (palagonite) in seawater is much faster than that of anhydrous, normal glass of similar composition (Bonatti, 1965).

Chemically these sediments are enriched in Mn and other ferrides, as mentioned in a previous section. These relations are well illustrated by study of the samples collected in the Amph D5 survey area and are discussed elsewhere in detail (Bonatti, 1967). The term "pelagic zeolite" has been proposed for the type of "red clay" influenced by deep sea hyaloclastic volcanism. Pelagic zeolites cover wide areas of the Southeastern Pacific and the Northwestern Pacific (Bonatti, 1967). The inorganic crystals of calcite contained in the zeolitic sediment closest to the base of the volcano at Station Amph D5, and the calcite and dolomite of sediment Chall 276, have been investigated in detail (Bonatti, 1966). Similar calcite crystals were found also along the East Pacific Rise. Their terrigenous origin is excluded. Oxygen isotopic analyses indicate their precipitation took place from a solution quite different from the deep seawater overlying the deposits in question, and suggest that they were precipitated as a result of hydrothermal activity related to local deep sea volcanism (Bonatti, *ibid.*).

**"Hyaloclastic" versus "quiet" volcanism.** Among dredging stations occupied during the first leg of the cruise "Amphitrite" two only were not on sea mounts, but were instead over hilly bottom. It is only at such stations (Amph D3 and Amph D4) that the rocks sampled consisted exclusively of basalts of quiet effusion type. Moore (1965) dredged and photographed pillow basalts of "quiet effusion" type from the east rift zone of the Kilauea volcano, at depths varying from 490 to 5000 meters below sea level, while rocks dredged by the same author from several close-by sea mounts show generally "hyaloclastic" features. Thus, lavas from quiet deep sea eruptions seem to be prevalently associated with hilly topography rather than with sea mounts.

The very frequent occurrence of rocks such as "palagonite tuffs" or hyaloclastites from among those dredged from sea mounts is documented quite extensively (Hamilton, 1956; Nayudu, 1962; Moore, 1965; present paper). The hypothesis that hyaloclastic rocks also fill up a substantial portion of the interior of sea mounts is supported by the low average density of sea mounts. Harrison and Brisbin (1959) suggested a density of 2.3 for Jasper sea mount (eastern Pacific), while for the island of Oahu a density of 2.3 to 2.5 has been proposed (Woollard, 1954). Hyaloclastic rocks derived from basaltic magmas have a much lower density than

massive basalts, due to the extensive hydration of their components and to their porosity. The fine hyaloclastite (c) described in Amph D5 has a density of 2.0, whereas the massive basalt from the same station has a density of 2.84. The low average density of sea mounts is explained if it is assumed that a substantial portion of their interior is occupied by hyaloclastites rather than massive basalts. Nayudu (1962) suggested that sea mounts are constituted by alternations of palagonite tuffs (hyaloclastites) and massive basalts, each alternation representing one effusive episode; the lava extruded first reacts with water and forms a carpet of hyaloclastites on the bottom, which prevents additional magma from directly meeting sea water, thus allowing it to cool into massive and at least partially crystalline basalt. This hypothesis may in part explain why massive lava is often associated with the hyaloclastites.

On the other hand it appears quite clearly from the description of dredge hauls Amph D3 and Amph D4 (present paper), or from the above-mentioned basalts off Hawaii (Moore, 1965), etc., that submarine lavas can give rise to massive, normal basalts even when they are erupted directly on the ocean floor without sedimentary or hyaloclastic layers insulating them from direct contact with seawater.

The question then arises as to why some basalts (Amph D3, Amph D4) erupt quietly on the ocean floor, without interaction with seawater, while others of similar composition and ejected at similar depths below sea level (Amph D5, Chall 276) strongly interact with seawater during the eruption.

A precise answer requires more investigation, and only some qualitative suggestions seem possible at present. Menard (1965, p. 57), referring to observations of various authors, points out that different lavas from the same volcano may enter the water differently, some quietly and others explosively, and quotes Stearns and MacDonald (1946) as concluding that in Hawaii blocky aa flows explode at the shoreline and only the fluid pahoehoe flows enter the water tranquilly. Aa and pahoehoe differ essentially in their viscosity (MacDonald, 1953). The viscosity of a lava depends, besides on its composition, on its gas content and temperature. In an erupting magma of basaltic composition the viscosity may vary by a factor of 10, depending on its temperature at eruption.

Among deep sea lavas described in the present paper those extruded "quietly" (Amph D3 and Amph D4) appear to have been ejected on the ocean floor while still completely liquid, as is indicated by their lack of first generation phenocrysts. This contrasts with the case of hyaloclastic lavas (Chall 276, Amph D5, Amph D1) whose crystalline portion is usually porphyritic and whose glassy portion contains abundant crystalline inclusions, indicating a lower temperature-higher viscosity at

eruption. These data suggest that in the deep sea as well the viscosity of the lava at the time of eruption may be the main factor determining whether a hyaloclastic or quiet ejection will take place. Very hot, fluid lava flows seem to react plastically to the sudden chilling action of cold water and to the instantaneous formation of a glassy crust, whereas more viscous basaltic melts react with explosive shattering.

Basaltic fissure volcanism, which usually is produced by high temperature, fluid lavas should, under these assumptions, give rise to quiet effusions on the ocean floor. Indeed Amph D3 lavas which are typical of "quiet" effusions, as was described earlier, are exposed over a wide area of sea bottom (figure 5), suggesting fissure volcanism. Basaltic lavas ejected by sea mounts should be relatively more viscous, being generally further removed from their original magmatic reservoir at the time of their eruption; this may partly explain the association of hyaloclastic volcanism with sea mounts.

Very high viscosities, such as are common in acidic magmas, should prevent any extensive formation of hyaloclastites. Only acidic lavas whose viscosities are lowered by a high gas content may produce hyaloclastites. In fact one case of hyaloclastites formed by a rhyolitic magma has recently been reported (Piehler, 1965). It is thus suggested that there is a range of viscosities of the lava at eruption time that is optimal for the development of hyaloclastic eruptions. Deep-sea basaltic lavas often erupt within this "optimal" range.

In addition to the temperature and viscosity of the erupting lava, other factors may be important in determining whether or not an eruption will produce hyaloclastites. The rate at which the lava comes in contact with seawater (that is, the volume of melt which flows out from a given vent per unit time) as well as the amount and type of motion of the seawater at the site of eruption may have to be considered in future attempts to quantitatively approach the problem of hyaloclastic versus quiet submarine volcanism (F. E. Wickman, personal communication).

### Summary and Conclusions

Figure 23 summarizes schematically some of the conclusions reached in the present paper. It is stressed again that the main difference between quiet and hyaloclastic activity is that in the former the interaction between hot lava and seawater during the eruption is minimal, whereas it is very extensive in the latter. This strong interaction is the cause of the processes which accompany hyaloclastic eruptions, processes which, in their turn, influence the chemistry and mineralogy of wide areas of

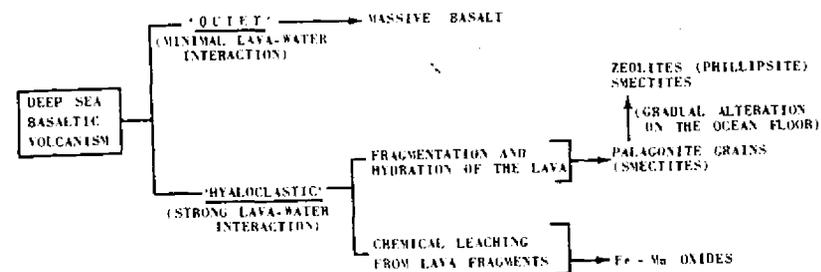


Fig. 23. Scheme of mechanisms of deep-sea volcanism.

the Pacific Ocean floor. Admittedly they are not well known yet, but their extensive study seems worthwhile.

Two suggestions based on data presented here may be pointed out.

1. Deep-sea basaltic rocks showing breccia and/or ash-like features must not necessarily have erupted under shallow water or above sea level, as is commonly believed.

2. The "altered" or "fresh" appearance of submarine basalts is not necessarily to be ascribed to the relative age or youth of the rock. In fact extensive "alteration" of submarine lavas may commonly take place rapidly at high temperature during the eruption, rather than gradually after emplacement, as is generally the case in subaerial formations. Deep-sea waters of the Pacific normally have a pH close to 7 and a rather constant low temperature, close to 0° C. Alteration of igneous minerals after emplacement under such conditions must be exceedingly slow, and concepts of "weathering" as learned in surface geology cannot be applied.

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