UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY

Preliminary petrology of igneous and sedimentary rocks recovered from central Pacific seamounts

by

Walter B. Friesen

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This report is preliminary and has not been reviewed for conformity with the U. S. Geological Survey editorial standards and stratigraphic nomenclature

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Abstract

Nine submarine volcanic structures in the central Pacific were studied on the Federal Republic of Germany's Midpac 2 Program. This program was designed to examine and assess the cobalt-rich ferromanganese crust resources in the central Pacific. Great abundances of volcanogenic and biogenic rock samples with thin to thick encrustations of ferromanganese oxide, in places enriched with small amounts of cobalt, nickel, and platinum, were recovered during two cruises by the R. V. Sonne, a research ship from the Federal Republic of Germany. The study areas visited are located in the Hawaiian, Line, and Phoenix Archipelagoes, and in the Mid-Pacific Mountains. Samples were recovered primarily between 1000m and 2000m water depth on the upper slopes and summits of the volcanic edifices. Rocks recovered are mainly breccias composed of alkalic basalt and its differentiates, trachyte and syenite, basaltic and differentiated lava hyaloclastite and tuff, and phosphatized calcarenite and chalk, or loose clasts of these breccia components. Lithic distribution on the seamounts suggests the following general eruptive sequence for the upper 1000m of the volcanic edifices: (1) alkali olivine basalt, (2) trachyte and differentiated alkalic lavas, and (3) subsilicic alkalic lavas. Most of the submarine volcanic edifices are guyots. Subsidence has gradually brought about their submergence to various depths. The inferred igneous eruptive sequence observed in the Midpac 2 seamounts is similar to that of the Hawaiian Islands-Emperor Seamounts chain and to that of other central Pacific linear island and seamount chains.

I. Introduction

An interesting variety of igneous and sedimentary rocks was recovered from nine central Pacific submarine volcanic edifices. These rocks commonly bear thin to thick encrustations of ferromanganese oxides and thin deposits of biogenic phosphorite. The ferromanganese oxide deposits are in places strongly enriched in the strategic metals cobalt, nickel, and platinum. The phosphorite has an interest potential to agriculture because of its high phosphorus and calcium content. A cooperative program between the United States and the Federal Republic of Germany was designed to study and assess the resource potential of the ferromanganese oxides and other seabed mineral deposits. The German part of the program is called Midpac and has included five research cruises. Midpac 1 (1981) surveyed submarine volcanic edifices in the northern Line Islands Archipelago and in the Mid-Pacific Mountains. Midpac 2A (1984) surveyed the same areas and also Cross Seamount south of Oahu Island. Midpac 2B (1985) surveyed submarine volcanic edifices south of Johnston Island in the Line Islands Archipelago and Titov Seamount southeast of Baker Island in the Phoenix Archipelago. Midpac 3/1 and Midpac 3/2 (1986) surveyed submarine volcanic edifices in the Marshall Islands Archipelago and in the Johnston Seamount Group south of Johnston Island, respectively. Rocks from the Midpac 2 study areas are the subject of this report. The regions surveyed were designated Areas "A" through "I" (Fig. 1). The West German research ship Sonne, under the scientific direction of Professor Peter Halbach of the Technical University of Clausthal, served as the work support vessel on Midpac 2A and 2B. Bottom photographs and videos, bathymetric data, and rock, ferromanganese oxide crust, water, and biological samples were collected from the study areas. The preliminary petrology of the rock samples is presented in the following pages. Locations and water depths of operations on Midpac 2A and 2B are summarized in Tables 1 and 2, respectively.

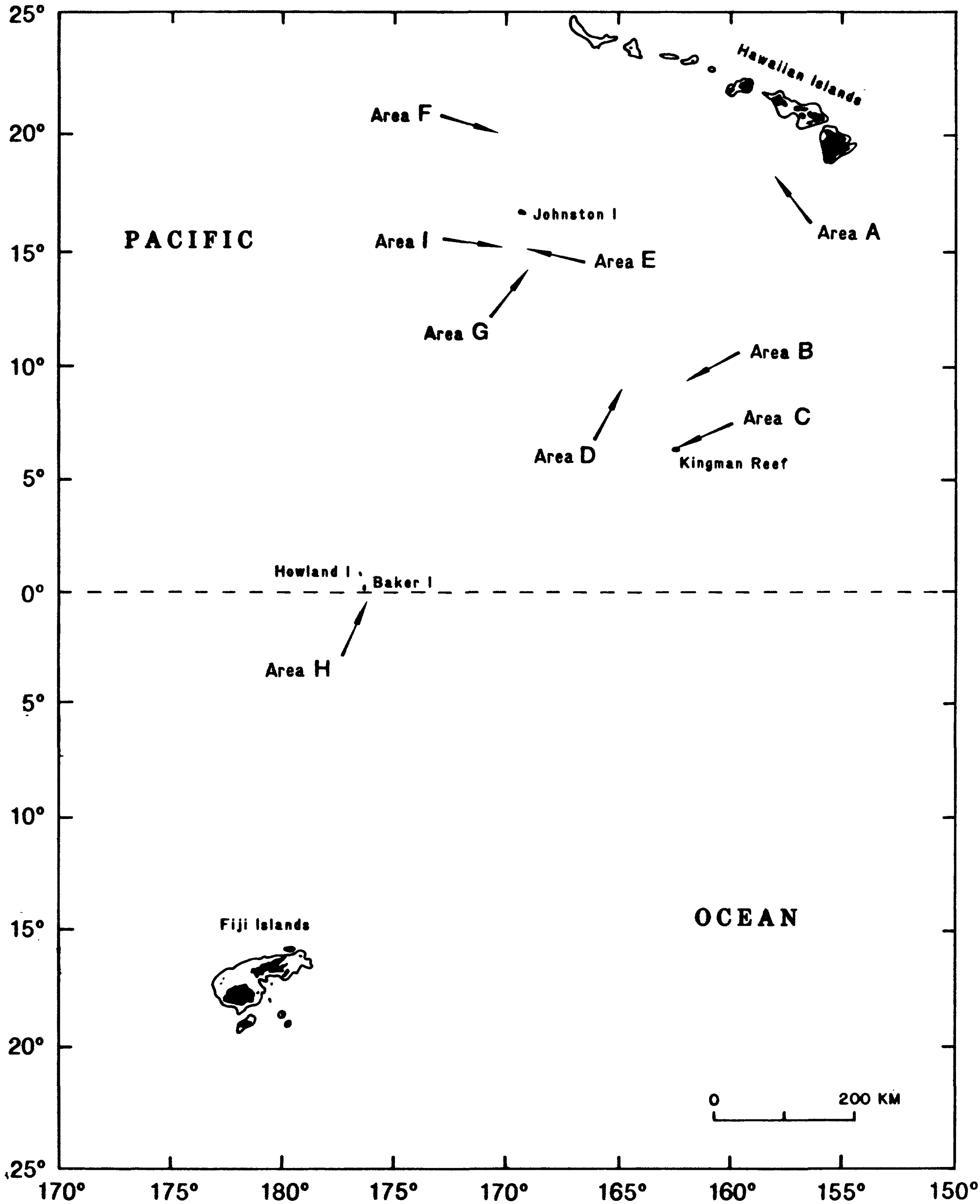

Figure 1. Area location map of Midpac 2 displaying study areas, reference islands and archipelagoes, and 1000fm contour (modification of a portion of "Central Pacific islands, reefs, and shoals" by Chase, Seekins, and Lund, 1984).

Table 1. Location coordinates and seabed data from Midpac 2A.

Area	Station	Average latitude	Average Longitude	Average water depth (m)	Length of dredge (km)+	Average slope angle (degrees)*
A	1 DK	18°41'40" N	158°22'54"W	4112	4.0	17
A	2 DK	18°39'07"N	158°17'59"W	2021	3.2	5
A	3 DK	18°38'03"N	158°18'56"W	2140	3.1	22
A	6 DK	18°40'59"N	158°18'46"W	870	1.0	51
B	8 DK	9°42'06"N	162°10'58"W	2262	4.4	13
B	9 DK	9°42'31"N	162°10'40"W	1793	5.2	4
B	15 DK	9°43'43"N	162°09'53"W	1487	3.8	6
B	17 DK	9°41'36"N	162°10'41"W	2448	4.6	11
B	18 DK	9°42'06"N	162°10'57"W	1755	1.4	23
C	24 DS	6°30'47"N	162°24'18"W	2154	4.2	10
C	25 DS	6°30'15"N	162°22'08"W	2619	2.5	13
C	29 DK	6°16'35"N	162°52'23"W	2788	3.6	14
C	30 DK	6°16'19"N	162°52'57"W	2045	3.4	23
C	31 DK	6°16'54"N	162°52'36"W	1418	1.1	12
C	33 DS	6°16'02"N	162°57'35"W	2714	3.2	12
C	34 DS	6°17'43"N	162°57'26"W	2021	4.3	16
D	37 DK	9°09'57"N	164°50'43"W	2366	2.1	2
D	38 DK	9°10'43"N	164°49'22"W	1637	2.1	15
D	39 DK	9°11'28"N	164°50'05"W	1217	3.9	2
D	40 DK	9°11'31"N	164°48'59"W	1267	8.5	2
D	41 DK	9°08'41"N	164°47'22"W	2348	4.0	13
D	42 DK	9°10'28"N	164°46'52"W	1721	2.9	16
D	43 DK	9°11'50"N	164°46'12 W	1502	1.3	16
D	44 DK	9°13'32"N	164°46'45"W	1464	1.6	1
D	47 DK	9°10'02"N	164°53'46"W	1388	5.2	8
D	48 DK	9°15'04"N	164°50'37"W	1324	3.0	3
D	49 DK	9°12'01"N	164°55'73"W	1350	-	-
E	55 DK	15°35'12"N	169°12'26"W	1477	1.5	13
E	56 DK	15°35'55"N	169°12'03"W	1387	3.0	4
E	57 DK	15°35'22"N	169°12'30"W	1209	2.4	7
E	58 DK	15°35'30"N	169°12'24"W	1332	2.2	3
E	62 DK	15°32'38"N	169°12'13"W	1728	3.3	5
E	63 DK	15°30'00"N	169°15'09"W	2905	3.7	6
E	64 DK	15°30'23"N	169°13'26"W	2161	2.7	22
E	66 DK	15°35'41"N	169°12'52"W	1432	0.6	31
F	69 DK	20°07'54"N	170°41'27"W	1496	0.8	5
F	71 DK	20°13'25"N	170°36'00"W	1997	2.1	55
F	72 DK	20°13'06"N	170°35'30"W	1548	1.2	15

+ Length of dredge determined from ship position when dredge on bottom and off bottom.

* Slope determined from bathymetric data.

Table 2. Location coordinates and seabed data from Midpac 2B.

Area	Station	Average latitude	Average longitude	Average water depth (m)	Length of dredge (km)+	Average slope angle (degrees)*
H	5 DK	0°22'24"S	176°05'10"W	1777	3.4	13
H	6 DK	0°24'10"S	176°07'30"W	1472	3.0	4
G	9 DK	14°27'75"N	169°00'65"W	1893	1.7	12
G	10 DK	14°27'34"N	169°59'09"W	1640	1.5	15
I	15 DS	15°41'00"N	170°21'00"W	1895	2.5	18
I	16 DS	15°40'68"N	170°21'75"W	1552	1.0	22
I	17 DS	15°40'63"N	170°22'34"W	1408	2.2	12
I	18 DS	15°39'22"N	170°24'52"W	2019	1.5	17
I	19 DS	15°40'66"N	170°24'26"W	1653	3.2	7
I	20 DS	15°39'92"N	170°23'50"W	1310	1.9	10
I	27 DS	15°38'44"N	170°23'62"W	1771	2.6	21
I	28 DS	15°38'67"N	170°23'71"W	1741	4.3	1
I	29 DS	15°39'70"N	170°21'80"W	1572	1.3	13
I	30 DS	15°39'91"N	170°22'86"W	1179	2.4	4
E	36 DS	15°36'90"N	169°13'33"W	1535	3.1	4
E	37 DS	15°34'00"N	169°12'52"W	1717	2.5	3
E	39 DS	15°37'47"N	169°06'95"W	2014	3.4	4
E	40 DS	15°38'11"N	169°05'42"W	3050	4.9	13
E	41 DS	15°38'05"N	169°07'00"W	2417	2.6	17
E	43 DS	15°32'64"N	169°13'68"W	1592	2.2	10
E	44 DS	15°37'28"N	169°12'64"W	1451	3.1	2
E	46 DS	15°35'60"N	169°12'64"W	1464	1.5	13
E	47 DS	15°38'40"N	169°15'35"W	1497	2.7	4

+ Length of dredge determined from ship position when dredge on bottom and off bottom.

* Slope determined from bathymetric data.

II. Geologic overview

1. Area A

Cross Seamount, a symmetrical volcanic cone with a nearly plane summit, was surveyed first on Midpac 2A (Fig. 2). Trachyte from this edifice has been dated by the K-Ar method at 78.8 to 85.5 my (Dymond and Windom, 1968). Volcaniclastic debris breccia and pyroclastic rocks composed of basalt, basaltic hyaloclastite, and trachyte occur as ferromanganese oxide-encrusted deposits on the slopes of the edifice. The summit is covered with calcareous foraminiferal ooze and ferromanganese oxide deposits. Rock samples were recovered in five dredge hauls from the southwest slope.

A. Petrography

Olivine/plagioclase-phyric basalt, commonly porphyry, occurs as clasts in the debris breccia recovered in three of the dredge hauls. Plagioclase dominates over olivine in some of the basalt and shiny black augite is commonly present as a microphyric phase. Textures are generally subtrachytic and intergranular, with small, round-to-oval, flow-oriented vesicles present in abundances rarely exceeding 30%. Vesicles are commonly lined with calcite and phillipsite druses. Clasts of both subaerially-erupted basalt and pillow basalt occur in the breccia. Subaerially-erupted basalt clasts are randomly vesicular and aa-like while pillow basalt clasts commonly have layers of flat vesicles and palagonite rinds.

Trachyte, abundantly phyric with sanidine, plagioclase, and biotite, is common as clasts in the breccia. It is commonly yellowish-gray or greenish-gray and has rare flecks of iddingsite after fayalite.

Basaltic hyaloclastite occurs abundantly in association with olivine basalt and the hyaloclastite commonly contains clasts of this basalt. Framework clasts and matrix grains are angular and composed of gravel-to-silt-size fragments of argillized basaltic glass froth. A much smaller amount of smectite-and-phillipsite cement binds the clastics and fills interstices. Sorting is generally poor.

Volcaniclastic debris breccia is composed of subangular-to-subrounded framework clasts of igneous and sedimentary rocks ranging in size from gravel through boulders. Matrix is generally lacking, the spongy-textured rock being cemented with phillipsite or apatite.

Foraminiferal calcarenite and phosphorite were recovered in two of the dredge hauls. The calcarenite is commonly very porous and friable, with an open, and in places spongy texture. Calcarenite grades into phosphorite as calcite is replaced by apatite, losing porosity and increasing in density. Some of the densest phosphorite has a porcellanous appearance. Most of the calcarenite and phosphorite contain a minor volcaniclastic component and are commonly cavernous with biogenic boreholes.

B. Alteration

Smectitic argillation, oxidation, zeolitization, phosphatization, solution, and recrystallization have affected the rocks of Cross Seamount. Hyaloclastite and phosphorite are the most altered and some types of basalt are the least altered rocks. Olivine is completely altered to iddingsite. The least altered mineral phases are biotite and its included zircons, and the separate phases augite and feldspars. Hydrothermal alteration is indicated by the partial oxidation of iron smectite in devitrified hyaloclastite and in deposits of metal oxides, calcite, and zeolites along fractures.

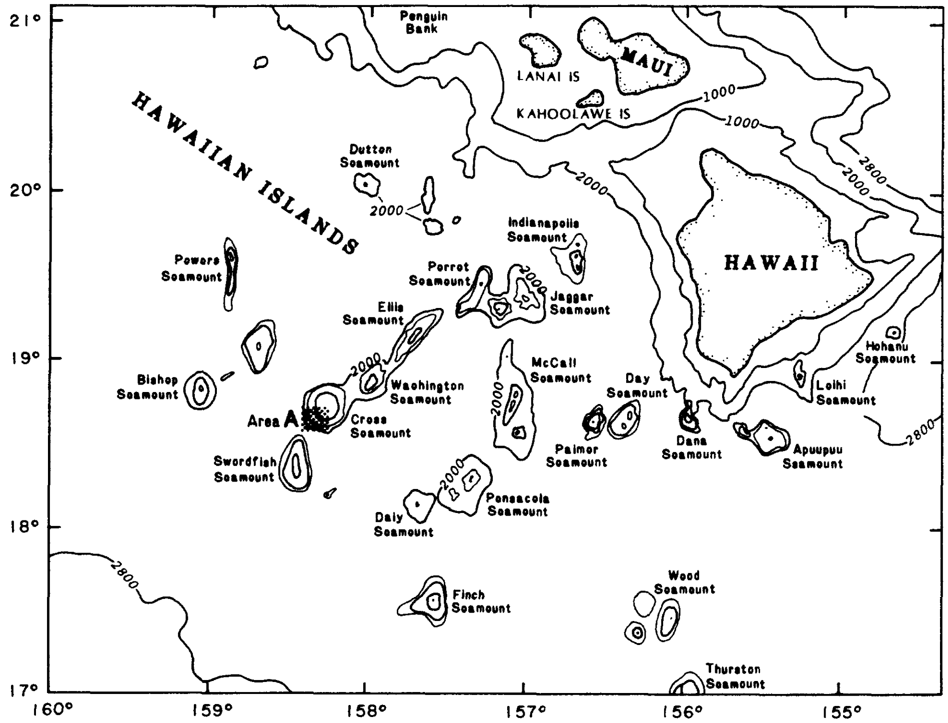

Figure 2. Location map showing Area A (stippled enclosure), Midpac 2A. Selected bathymetric contours (measured in fathoms) included for reference. Modified from Menard and Chase (1971).

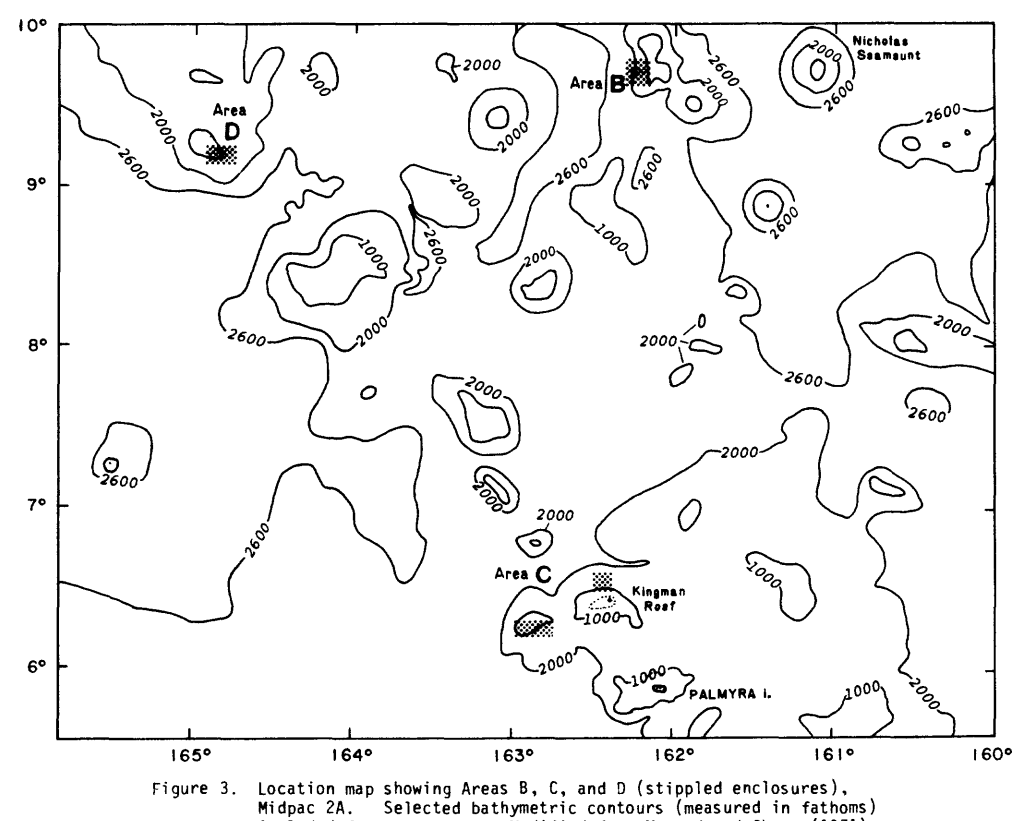

Figure 3. Location map showing Areas B, C, and D (stippled enclosures), Midpac 2A. Selected bathymetric contours (measured in fathoms) included for reference. Modified from Menard and Chase (1971).

C. Lithic distribution

Rock and sediment samples were recovered from near the base of Cross Seamount to the summit. Red clay was recovered in the deepest dredge haul and calcareous foraminiferal ooze was recovered from the shallowest. Volcaniclastic debris breccia, the most abundant rock type recovered, probably covers the slopes of the cone extensively. Fragments from subaqueous hyaloclastite eruptions are incorporated in the volcaniclastic debris sampled in most dredge hauls. Debris breccias sampled near the summit contain igneous rock clasts that are subrounded-to-rounded. Some samples of breccia display crude graded bedding. Samples of calcarenite and phosphorite were recovered in dredge hauls from the higher slopes of the seamount.

2. Area B

After Cross Seamount, an unnamed guyot complex north of Kingman Reef in the Line Islands Archipelago was surveyed on Midpac 2A (Fig. 3). Rock samples similar to those recovered from Cross Seamount were found at five dredge sites on the southwest slope and summit of the prominent middle lobe of the guyot complex, between 1300m and 2500m water depth.

A. Petrography

Olivine/plagioclase-phyric basalt is the most abundant igneous rock occurring in volcaniclastic debris breccia, the most abundant rock type in the dredge recovery. Fragments of pillow basalt found in the breccia commonly have palagonite rinds and generally a greater abundance of plagioclase over olivine phenocrysts. Subaerially-erupted basalt clasts have a greater abundance of olivine over plagioclase phenocrysts. Phenocryst and vesicle sizes, shapes, abundances, and distributions are similar to those of the basalts of Cross Seamount, and the textures are also similar.

Basaltic hyaloclastite is abundant in the recovery and resembles that found on Cross Seamount. Grains are generally subangular and equant, and sand-size.

Some samples of volcaniclastic siltstone and marl display distinct stratification, good sorting, and have bedding planes that are marked with ferromanganese micronodules. The marl is burrowed.

Volcaniclastic debris breccia has a variety of included rock clasts, cement types, and textures. Some samples display crude graded bedding. The textures are generally open and spongy, and subrounded framework clasts occur infrequently among the usual subangular ones. Cement is calcite or apatite and is sparing.

Rare foraminiferal calcarenite is very porous and friable. Silt-size basaltic glass shards and ferromanganese micronodules mark otherwise indistinct bedding planes.

B. Alteration

Smectitic argillation and oxidation are the most pervasive types of alteration. Other processes include zeolitization, solution, redeposition, and phosphatization. Olivine is completely altered to iddingsite but plagioclase is little altered. Glass is substantially devitrified to smectite and zeolites; pillow basalt chilled glass rind is completely palagonitized. Pillow basalt clasts commonly display aureole-like zones of hydrothermal alteration along fractures. These zones are commonly wide and are rich in smectite and iron oxide. Some subrounded cobbles of subaerially-erupted basalt have zones of peripheral alteration due to weathering. Hyaloclastite is altered in a similar way to that found on Cross Seamount. Phosphatization in calcareous rocks ranges from slight to complete.

C. Lithic distribution

The topography of the Area B guyot complex is dominated by rough cliff-and-terrace structure and numerous outcrops of pillow lava are apparent in bottom photographs. Most of the igneous rock recovery is from slope-and-terrace-draping debris. Localized eruptions of hyaloclastite have contributed to the composition of the breccias. The numerous terraces on the slopes and the extensive summit of the main guyot served to accumulate deposits of clastic debris, biogenic carbonate sediment, and ferromanganese oxide nodules and crusts. Rare samples of basaltic tuff and tuffaceous marl were recovered from the periphery of the summit of the main guyot.

3. Area C

The coalesced submarine volcanic edifices crowned by Kingman Reef in the Line Islands Archipelago werethe next study area of Midpac 2A (Fig. 3). The north slope of the seamount crowned by Kingman Reef and the southwest slope and the summit of an unnamed guyot just southwest of Kingman Reef were examined between 1300m and 2953m water depth. Numerous types of uncommonly fresh basaltic rock were recovered. Also recovered were samples of basaltic hyaloclastite and tuff, tuffaceous marl, foraminiferal calcarenite, and phosphorite. Structurally, the complex displays rough cliff-and terrace topography which increases in average slope with decreasing water depth. Bottom photographs reveal numerous overhanging cliffs.

A. Petrography

Olivine basalt is the most abundant rock type, occurring mostly as clasts in volcaniclastic debris breccia. Some of the basalt samples recovered probably come from primary outcrop also. Both pillow lava and subaerially-erupted lava clasts are abundant components of the breccia. Some of the rock samples may be vent agglomerates and some may be trap. The basalt is similar in appearance to that recovered from Areas A and B. Differences are mainly in phenocryst abundances and proportions. Basalt in which plagioclase is more abundant than olivine is rare. Some samples have olivine and pyroxene phenocryst contents in excess of 30 percent.

Basaltic hyaloclastite was rarely recovered. Hyaloclastite from the guyot southwest of Kingman Reef is especially rich in iddingsitized olivine, plagioclase, and emerald green pyroxene.

Basaltic tuff likewise was rarely recovered. A well-sorted ash tuff was dredged from off Kingman Reef and a cinder tuff and a tuffaceous marl were recovered from the guyot to the southwest of Kingman reef.

Volcaniclastic debris breccia, resembling that recovered from Areas A and B, is the most abundant lithology; it is composed mainly of various basalt types. Minor constituents include pyroclastic rocks and calcareous biogenic rocks.

Foraminiferal calcarenite with extensive biogenic boreholes and phosphatized calcarenite with a small volcaniclastic component were recovered from the guyot. These rocks display the striking variations observed in the phosphatization of carbonate deposits from the deep marine environment of the central Pacific.

B. Alteration

Smectitic argillation, oxidation, zeolitization, solution, redeposition, and phosphatization are the processes that have affected the the rocks of Area C. Alteration is extensive, but some types of basalt and calcarenite are only superficially altered. Most olivine is altered to iddingsite, but some basalt has unaltered phenocrysts of olivine. In some basalt, olivine is altered to a mixture of smectite and calcite. In other basalt, this type of alteration is concomittant with alteration to iddingsite. Plagioclase and pyroxene are superficially altered to smectite, iron oxide, and zeolites. Iron and manganese oxides, dark green nontronite, and druses of calcite and phillipsite are abundant along fractures in basaltic rocks. Iron oxides abundantly penetrate the porous rocks encrusted with ferromanganese oxides. Phosphatization is differential in the carbonate rocks. Phosphatization in the calcareous cement of volcaniclastic debris breccia is generally greater than in primary carbonate deposits.

C. Lithic distribution

The numerous structural terraces on the submarine volcanic edifices of Area C have accumulated clastic debris, biogenic sediment, and ferromanganese oxide deposits. Outcrops of pillow lava are apparent in bottom photographs. Deposits of clastic debris are apparently less abundant in Area C than in Areas A and B. Abundant coral and shell debris were recovered from the upper slopes of the seamount crowned by Kingman Reef. Basaltic debris breccia, hyaloclastite, and vitric tuff were recovered at greater depth. The great variety of igneous rocks recovered from the unnamed guyot attests to the great activity of the volcano over a relatively brief period during its formation.

4. Area D

The south slope and summit of a small, unnamed guyot northwest of S. P. Lee Guyot in the Line Islands Archipelago was surveyed after Kingman Reef on Midpac 2A. (Fig. 3). Rock samples were recovered from eleven dredge sites at water depths from 1095m to 2750m. Volcaniclastic debris breccia, basalt, basaltic hyaloclastite, tuff, and phosphorite were recovered. Terraced topography is apparent in bottom photographs.

A. Petrography

Basalt-laden volcaniclastic debris breccia was the most abundant rock type recovered. Basalt clasts in the volcaniclastic debris breccia are typically olivine microphyric with phenocryst abundances ranging from less than one percent to about 20 percent. The basalt is commonly scoriaceous. Some of the basalt is sparingly microphyric with plagioclase and augite. Groundmass texture is generally intergranular. The volcaniclastic debris breccia is similar in texture and physical properties to that recovered from Areas A, B, and C. Framework clasts are commonly subangular but also subrounded, and matrix is commonly composed of fine shell debris and basalt detritus.

An unusual basaltic hyaloclastite was recovered. The highly scoriaceous framework clasts are dark brownish-red and gravel size.

Three types of tuff were recovered. They are composed of well-stratified sand-to-gravel-size particles and are cemented with smectite.

Few calcareous or phosphatic rocks were recovered. Samples include a highly porous, bioturbated, and bored foraminiferal calcarenite, and a spongy, massive, undisturbed foraminiferal calcarenite.

B. Alteration

Rocks recovered from Area D are extensively altered. Smectitic argillation, oxidation, zeolitization, phosphatization, and carbonation have acted on the rocks. Ferromagnesian minerals are commonly altered to hematite and calcite. Olivine is usually altered to hematite and calcite or to iddingsite. One dredge had basalt with unaltered olivine phenocrysts, however. Plagioclase and augite are superficially altered.

Calcite and zeolite veinlets with aureoles of alteration frequently crosscut basalt but contain no metallic mineral phases. The aureolic zones are highly smectitic.

Volcaniclastic rocks are extensively argillized to smectite and zeolitized. The framework clasts are bound with calcareous cement which is extensively altered to apatite. Many of the subrounded basalt framework clasts have deep weathering rims.

C. Lithic distribution

The general topography of the guyot is more subdued than that of the preceding study areas. Numerous intervening slopes between cliffs and terraces create a more gentle terrain than that encountered in other seamounts. Olivine basalt is the most abundant igneous rock encountered in breccia outcrops between 1500m and 3000m water depth on the guyot. Numerous exposures of pillow basalt are apparent in bottom photographs, not having been completely covered with clastic material. Plagioclase/augite-phyric basalt occurs in the dredge recovery from near the summit, from whence also come foraminiferal calcarenite and phosphorite.

5. Area E

About one degree latitude south of Johnston Island in the Line Islands Archipelago is the Johnston Seamount Group. This volcanic ridge is terminated on the east by a large guyot with an extensive summit. The south and southeast portions of the summit, summit rim, and upper slopes of this edifice were examined on Midpac 2A and 2B and designated Area E for both cruises (Fig. 4). Twelve dredge sites on Midpac 2A and ten on Midpac 2B recovered abundant basaltic hyaloclastite and smaller amounts of basalt, trachyte, volcaniclastic debris breccia, tuff, marl,calcarenite, and phosphorite from water depths of from 1278m to 3050m.

A. Petrography

Olivine-phyric pillow basalt and subaerially-erupted basalt with subordinate plagioclase and augite phenocrysts are abundant constituents of numerous types of volcaniclastic debris breccia recovered from Area E. Plagioclase is commonly the the dominant phenocryst phase in subaerially-erupted basalt. Some basalt is sparingly microphyric with aegirine-augite alone or microglomerophyric with plagioclase. Some basalt also contains phenocrysts of transparent brown augite. Groundmass textures are subtrachytic and intergranular to hyalopilitic. Subaerially-erupted basalt is commonly vesicular throughout while pillow basalt has large flat vesicles in layers with intervening dense zones. Some basalt is abundantly phyric with olivine and augite and it is dense and without directed texture.

Hyaloclastite from Area E resembles that recovered from Areas A through D. Unique to Area E is hyaloclastite with stratification, differing strikingly from the usual massive, structureless texture.

Volcaniclastic debris breccia composed mostly of fragments of hyaloclastite varieties was abundantly recovered on both Midpac 2A and 2B. Clasts of angular-to-subrounded basalt and carbonate/phosphate sedimentary rocks are minor constituents of the breccia. As in most Midpac 2 study areas, breccia is the source of most igneous rock samples. Other than for the great abundance of reworked hyaloclastite as framework clasts, the petrographic properties of the Area E breccias are similar to those of breccia recovered from other Midpac 2 study areas.

Basaltic tuff and phosphatized tuffaceous marl were rarely recovered. These rocks are commonly thin deposits interbedded with phosphatized calcareous rocks. In places, the grain size is commonly in the silt range.

Trachyte was recovered on Midpac 2A only. It is sparsely phyric with sanidine and aegirine and occurs as angular clasts in a monolithlogic rubble breccia.

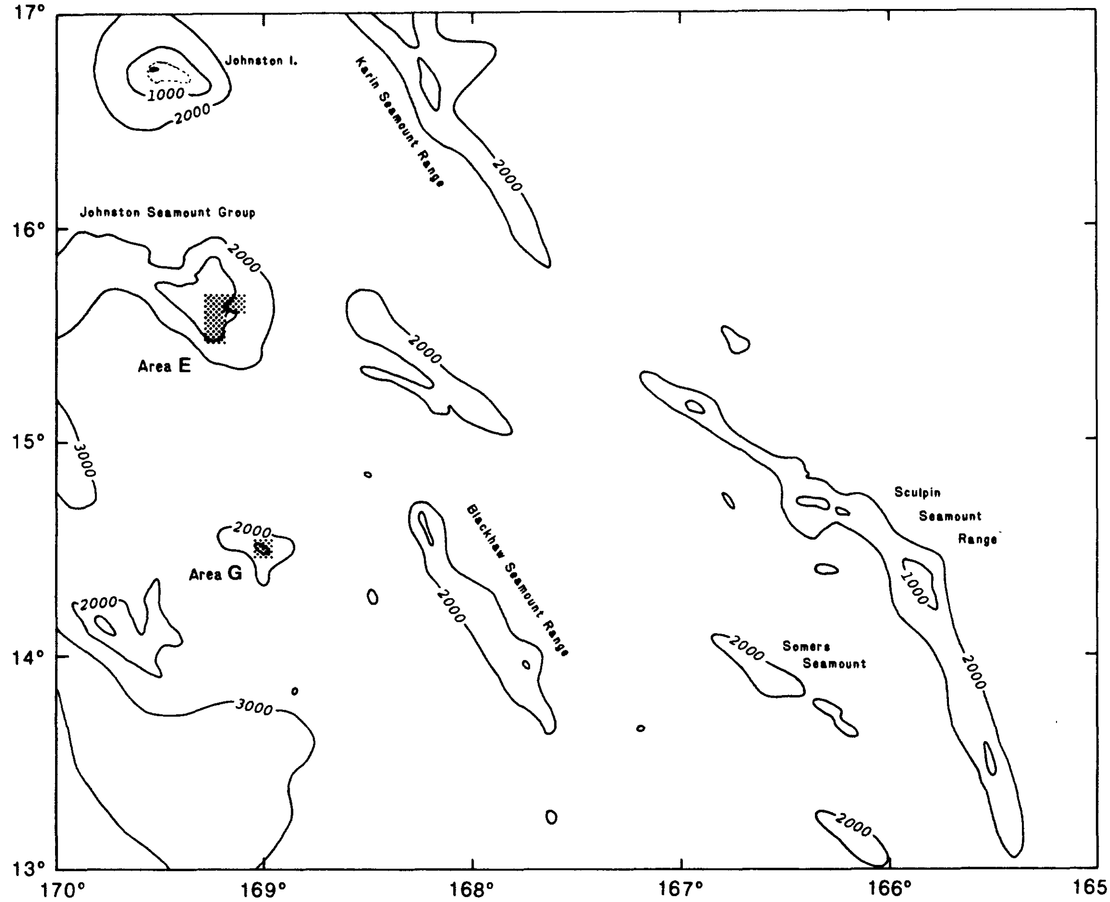

Figure 4. Location map showing Areas E and G (stippled enclosures), Midpac 2A and 2B. Selected bathymetric contours (measured in fathoms) included for reference. Modified from Menard and Chase (1971).

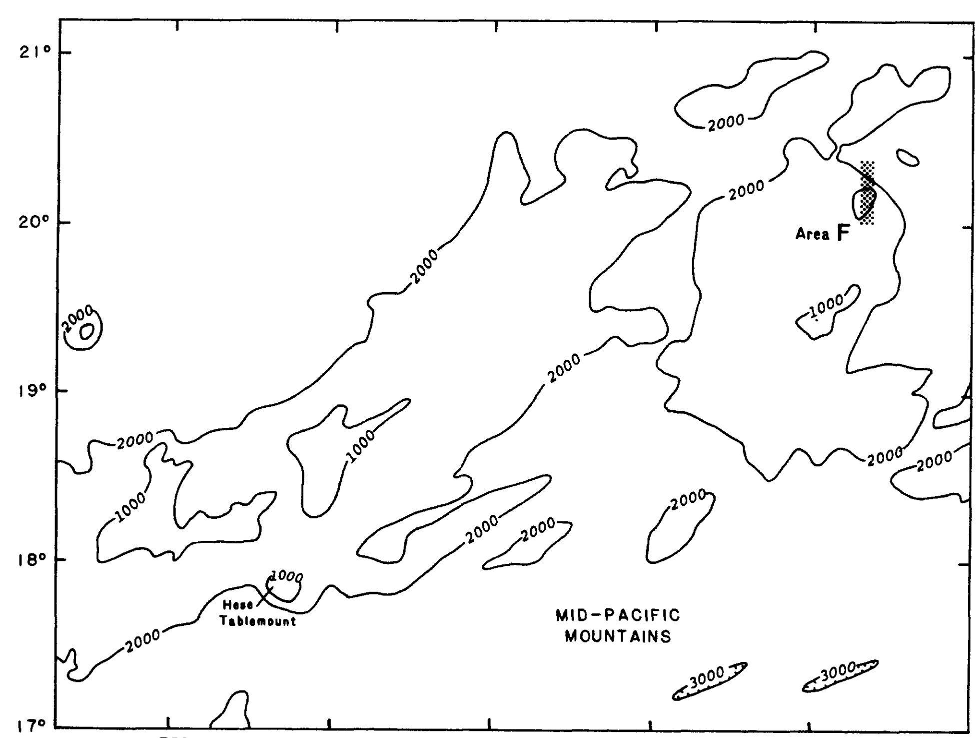

Figure 5. Location map showing Area F (stippled enclosure), Midpac 2A. Selected bathymetric contours (measured in fathoms) included for reference. Modified from Menard and Chase (1971).

Phosphatized calcarenite is rare and commonly has a porous to spongy texture. The rock commonly has a minor volcaniclastic component which ranges from silt to sand in size. Rare chalk in places displays faint stratification and in other places distinct bedding highlighted by volcaniclastic grit. The rock is commonly friable and poorly cemented but the original grains, which were probably nannofossils such as coccoliths, have been altered beyond identification by recrystallization. Some highly phosphatized foraminiferal calcarenite is dense, indurated, and porcelain-like, commonly laced with sinuous worm tubes and volcaniclastic debris ranging from silt to pebble size.

B. Alteration

Though some chalk appears to be unchanged and some basalt is fairly fresh, most Area E rocks are extensively altered. Smectitic argillation, oxidation, zeolitization, phosphatization, solution, recrystallization, and carbonation have acted upon the rocks. Feldspars are variously argillized and zeolitized. Pyroxenes are commonly fresh but some are well-altered to smectite and iron oxide. Though fresh olivine phenocrysts were encountered in a few pillow basalts, olivine is commonly altered to iddingsite. Glass is commonly altered to smectite and iron oxide.

Trachyte and hyaloclastite are extensively altered to zeolites, smectite, and iron oxide. Many of the igneous rocks are partially altered to the smectite phase nontronite, which colors them various shades of yellow-green.

Volcaniclastic debris breccia is extensively penetrated and encrusted with phillipsite and other zeolites. Calcareous cement is extensively altered to apatite.

The volcaniclastic component of tuff and marl is extensively altered to smectite and phillipsite. Carbonate component is variously phosphatized.

Phosphatization is commonly extensive in carbonate rocks. Dense phosphorite forms the matrix of some breccia and the cement is apatite.

C. Lithic distribution

Bottom photographs of the Area E guyot show a broad, extensive summit studded with small volcanic cones. The highest elevation on the guyot is a large domical volcanic structure near the southwest edge. The main edifice of the guyot has an irregular shape which suggests that it may be an aggregate of large volcanic cones. Most dredge hauls from Area E of both Midpac 2A and 2B are from the summit of the guyot or from the upper slopes and thus the samples are not representative of the whole edifice. A large variety of hyaloclastite and volcaniclastic debris occurs in relatively small areas sampled in the dredge hauls. Volcaniclastic rock composed mainly of olivine-phyric basalt is dominant at the summit of the guyot whereas volcaniclastic rock composed mainly of augite/plagioclase-phyric basalt is dominant on the volcanic edifices surmounting the main edifice. Distinctly stratified hyaloclastite was recovered from what appears to be a rift in the east side of the summit. Pillow basalt containing fresh olivine phenocrysts was also recovered from the same area. Trachyte was recovered only at the southernmost extremity of the summit of the main guyot edifice. Ferromanganese oxide in places thickly encrusts volcaniclastic debris and biogenic sedimentary rock outcrops. Many subrounded, deeply weathered clasts of subaerially-erupted lava occur with unweathered, angular lava clasts in the breccia, testifying to the extensive transport of rock detritus from the summit and down the flanks of the edifice in the past. Phosphorite is commonly interbedded with the carbonate deposits which partially cover the breccia.

6. Area F

The southeast slope of a small, unnamed volcanic edifice near Hess Tablemount in the Mid-Pacific Mountains was the last study area of Midpac 2A (Fig. 5). Dredge hauls were taken from five sites at water depths between 1496m and 1997m. Volcaniclastic debris breccia composed of basalt, basaltic hyaloclastite, basaltic tuff, trachyte, calcarenite, and phosphorite were recovered. Subdued cliff-and-terrace structure dominates the topography of the edifice.

A. Petrography

Volcaniclastic debris breccia and conglomerate composed primarily of basalt framework clasts and matrix are the most abundant rock types recovered. Basalt clasts are sparingly plagioclase/augite-phyric in both phenocrysts and glomerocrysts. Microphenocrysts of ilmenite are common. Groundmass textures are intersertal to intergranular and commonly subtrachytic. Vesicles are commonly round to elliptical, devoid of mineral deposits, strongly flow-oriented, and vary greatly in abundance over the space of a few millimeters. Much of the basalt is aa-like in gross texture.

Trachyte, commonly dark gray, is sparingly phyric with sanidine, plagioclase, amphibole, and biotite. Voids in the groundmass of some specimens are filled with biotite.

Basaltic hyaloclastite was rarely recovered. Generally, its physical properties resemble those of hyaloclastite recovered from other Midpac 2 submarine volcanic edifices. The hyaloclastite from Area F differs from most others recovered in its abundant apatite cement.

Volcaniclastic debris rocks are similar in their physical properties to the clastic rocks of other Midpac 2 study areas. Commonly, subrounded igneous rock framework clasts and abundant matrix composed of foraminiferal tests and mollusk shell fragments are firmly cemented with apatite to make up the various types of breccia and conglomerate.

Punky, cavernous foraminiferal calcarenite is the only primary sedimentary rock in the dredge haul recovery. Other calcareous rocks, some of them tuffaceous, are highly phosphatized, indurated, and dense.

B. Alteration

The rocks of Area F are affected by oxidation, smectitic argillation, phosphatization, and zeolitization. Matrix and cement in volcaniclastic debris breccia and conglomerate have been zeolitized and highly phosphatized. Feldspar phases in both basalt and trachyte are superficially altered to smectite and zeolites. Amphibole, with few exceptions, is completely altered to smectite and iron oxide. Augite, biotite, and opaque phases are slightly altered. Groundmass glass is devitrified. Phosphatization in calcareous rocks is extensive.

C. Lithic distribution

Bottom photographs display extensive deposits of ferromanganese oxide encrustations under which may be large deposits of volcaniclastic debris on slopes and terraces. Outcrops of pillow lava are apparent in bottom photographs taken between 1359m and 1674m water depth, but samples of these outcrops were not recovered. Broad terraces on the slopes of the guyot are littered with ferromanganese oxide-encrusted talus or blanketed by calcareous ooze dotted with vast numbers of pebble-size, warty-textured ferromanganese oxide nodules which have igneous or phosphate rock nucleii. Most of the igneous rocks were erupted subaerially as flows and were weathered and comminuted before the submergence of the guyot. Calcareous sediment abounds on the terraces and summit of the guyot, but calcareous and phosphatic rocks were rarely recovered.

7. Area G

A small, unnamed seamount located about one degree latitude southeast of Area E was surveyed as the second study area of Midpac 2B (Fig. 4). Clasts of basalt, basaltic hyaloclastite, trachyte, volcaniclastic debris breccia and sandstone, and foraminiferal calcarenite were recovered from two sites located on the southwest side of the steep cliff-and-terrace sculptured edifice between 1640m and 1893m water depth.

A. Petrography

Most of the rocks recovered are clasts derived from volcaniclastic debris breccia. Two basalt types in the breccia are nearly aphyric, having olivine and augite microphenocrysts together in one type and olivine microglomerocrysts only in the other. Groundmass textures in both basalt types are intergranular, but one type is highly vesicular and the other is dense.

Very rare basaltic hyaloclastite including pieces of vesicular basalt was recovered in the deepest dredge haul. It is similar in its physical properties to hyaloclastite recovered from other Midpac 2 study areas.

Three types of trachyte were recovered, each distinctly different. One type is aphyric and composed almost completely of sanidine; another is microphyric with rare sanidine phenocrysts and has an abundance of fine, acicular aegirine in the groundmass; the third is microglomerophyric with sanidine and biotite, making a spotted or paisanitic texture. A basalt xenolith was found in one specimen of the trachyte last described.

Volcaniclastic debris breccia is composed of a variety of igneous and sedimentary rocks. Some of the breccia contains trachyte clasts only, some contains basalt clasts only, and some contains a mixture of the angular-to-subrounded components. Some of the breccia contains clasts of phosphorite as well as the igneous components described above. The porous, open-textured clastics are cemented with apatite and calcite. A very rare, poorly-sorted volcanic arenite composed of basalt and trachyte framework grains and matrix, and cemented with apatite was found in the dredge recovery.

Rare, very porous, phosphatic foraminiferal calcarenite was found in the dredge haul recovery. Unlike many similar rocks, this calcarenite is lacking stratification.

B. Alteration

Most rocks recovered from Area G are extensively altered, affected by smectitic argillation, oxidation, zeolitization, solution, phosphatization, and carbonation. Basalt is extensively altered to smectite and brown iron oxide, and no fresh olivine remains. Groundmass plagioclase is commonly zeolitized. The groundmass of sanidine/biotite trachyte is replaced with smectite, calcite, apatite, and iron oxide. Sanidine/aegirine trachyte is relatively unaltered. Hyaloclastite is completely altered to smectite, zeolites, and brown iron oxide. Dense deposits of phillipsite and calcite euhedra commonly line open spaces in breccia. Phosphatization is extensive in calcareous rocks.

C. Lithic distribution

The topography of the seamount as revealed in bottom photographs is very rough, dominated by high relief cliff-and-terrace structure. Sediments have accumulated on narrow, shelf-like plateaus at different depths on the seamount flanks. Subrounded clasts of basalt, probably erupted subaerially, are comingled with subrounded trachyte clasts in the volcaniclastic debris breccia recovered from the terraces and plateaus. The greatest abundance of trachyte was recovered at greater elevation on the seamount. Volcanic arenite similar in composition to the breccia was also recovered at greater elevation on the seamount. Phosphatized calcarenite was recovered at lower elevation.

8. Area H

Titov Seamount, just southeast of Baker Island in the Phoenix Archipelago, was the first study area of Midpac 2B (Fig. 6). Igneous rock clasts, ranging in composition

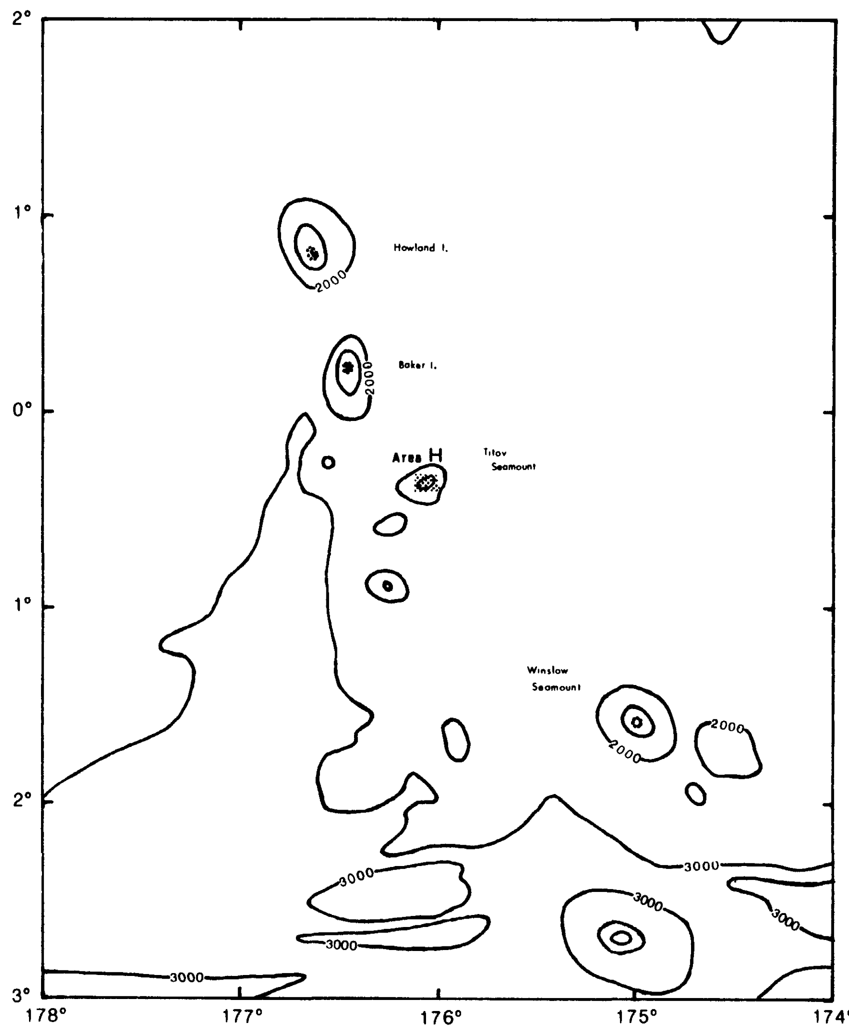

Figure 6. Location map showing Area H (stippled enclosure), Midpac 2B. Selected bathymetric contours (measured in fathoms) included for reference. Modified from Menard and Chase (1971).

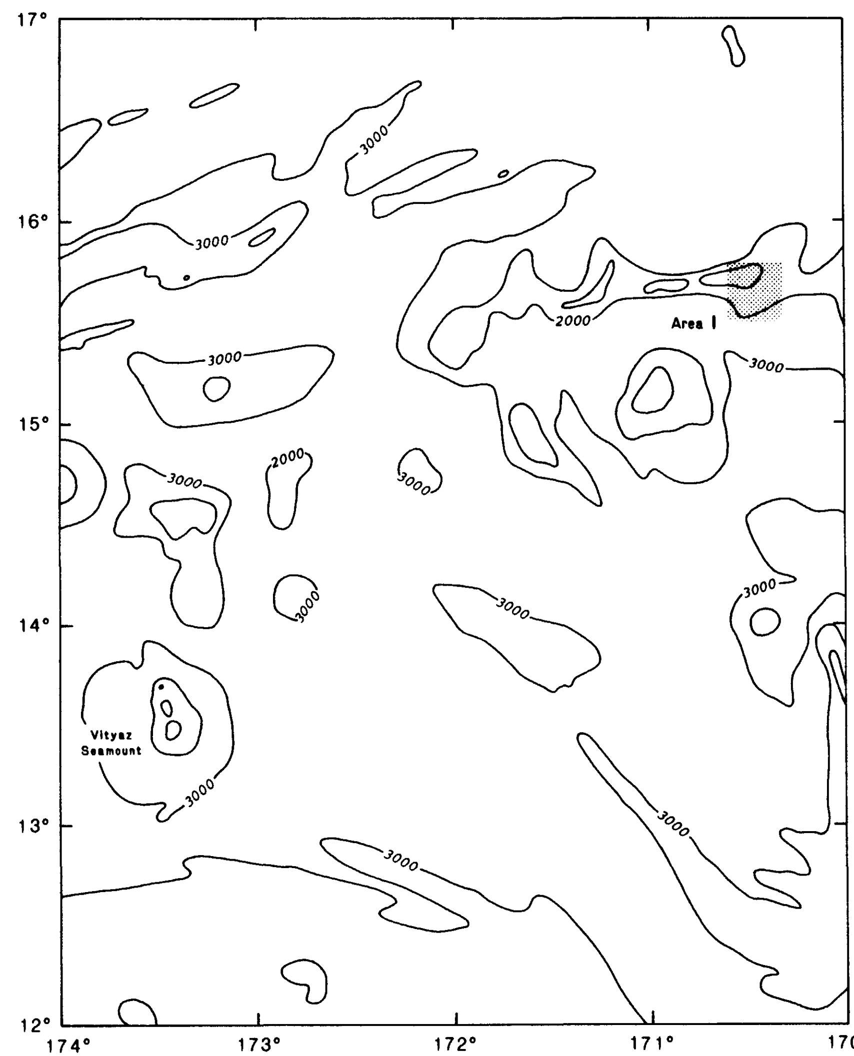

Figure 7. Location map showing Area I (stippled enclosure), Midpac 2B. Selected bathymetric contours (measured in fathoms) included for reference. Modified from Menard and Chase (1971).

from basalt through trachyte and felsic intrusives, together with basaltic hyaloclastite, calcarenite, coquinite, and phosphorite clasts make up various types of volcaniclastic debris breccia which are the main lithology of rock outcrops at the dredge haul sites. Two dredge hauls were made on the flanks of the crescent-shaped guyot between 1472m and 1777m water depth: one on the east flank and one on the west flank.

Basalt of the recovery is abundantly to sparingly phyric. Three basalt varieties have olivine and/or augite phenocrysts and three varieties have plagioclase, olivine, augite, and hornblende phenocrysts and glomerocrysts. Groundmass textures are generally intergranular and subtrachytic, and non-vesicular. A clast of pillow lava proved to be a densely porphyritic olivine basalt. Other varieties of basalt have an aa-like gross texture and have abundant scoria inclusions. These types of basalt may have been erupted subaerially. Hornblende-bearing basalt is non-vesicular and occurs as inclusions in hornblende-bearing basaltic hyaloclastite.

Basaltic hyaloclastite varieties fall under two main headings: olivine basalt hyaloclastite and plagioclase/augite/hornblende basalt hyaloclastite. The hyaloclastite varieties contain inclusions of their parent lavas. The olivine basalt hyaloclastites resemble those recovered from other Midpac 2 study areas. The hornblende-bearing hyaloclastite varieties are quite different, being generally much less altered and bearing up to 25% euhedra of augite, hornblende, plagioclase, ilmenite, and sphene.

Clasts of two types of sanidine/hornblende/augite/biotite syenite were encountered in the hornblende-bearing hyaloclastite: one type has an even, granitic texture and the other is hornblende-phyric with reaction rims of biotite on the phenocrysts.

Volcaniclastic debris breccia contains or consists entirely of hyaloclastite fragments. Some clasts contain abundant fragments of igneous and sedimentary rocks as well. The breccia varieties are commonly of low porosity. Framework clasts are generally subangular, but subrounded clasts are also encountered. Grainsize ranges from silt through boulders. Sorting is very poor.

Foraminiferal calcarenite, coquinite, and phosphorite were rarely recovered. The rocks are highly porous, with the porosity decreasing and density increasing in phosphorite. Coquinite is a poorly-sorted mix of subangular, coarse sand-size mollusk shell-and-coral reef debris loosely cemented with calcite. Foraminiferal calcarenite is cavernous with biogenic borings and has a spongy, honeycomb texture.

B. Alteration

The range of alteration in the Titov Seamount dredge haul rocks is from minor through extensive. The processes of alteration are smectitic and kanditic argillation, oxidation, zeolitization, phosphatization, solution, amphibolization, and biotitization. Olivine is altered to iddingsite, chlorophaeite, and calcite. Many olivine phenocrysts replaced with calcite are skeletal because of subsequent leaching. Alteration of feldspar phases is generally slight, but in one of the syenites, zeolitization and kaolinitization are apparent. Augite is variably amphibolized in the syenites and in some basaltic rocks. Biotite partially replaces hornblende in the syenites. Phillipsite and calcite commonly encrust voids in volcaniclastic rocks. Glass is altered to smectite, brown iron oxide, and zeolites. Solution and phosphatization have altered the carbonate rocks. Some phosphatized calcarenite has drusy apatite deposits surmounting a patina of remobilized iron-and-manganese oxide that coats the walls of biogenic boreholes.

C. Lithic distribution

Titov Seamount is arcuate in shape with a small, plane crescentic summit surmounted at the southern end by a small, domical volcanic cone. The summit has a thin cover of calcareous foraminferal ooze which is underlain by dense, phosphatized ferromanganese oxide and dense amber-like phosphorite. No igneous rocks were recovered from the summit, but igneous rock debris constitutes the bulk of the dredge haul recovery from the seamount slopes. Olivine-phyric basalt occurs frequently in the clastic rocks recovered from farther down the flanks of the seamount while plagioclase/augite/hornblende-phyric basalt and felsic igneous rocks are more abundant components of the clastic rocks recovered from near the summit. Olivine basalt and hornblende-bearing basalt hyaloclastites occur in both dredge hauls. Coquinite, calcarenite, and phosphorite were recovered from the summit area.

9. Area I

The east, west, and southwest slopes, and the summit of the highest guyot in the Johnston Seamount Group were surveyed as the last study area of Midpac 2B (Fig. 7). A large variety of igneous rocks ranging from basalt through trachyte were found as clasts in volcaniclastic debris breccia recovered from water depths ranging from 1179m to 2019m. Alkali olivine basalt and hawaiite hyaloclastites, syenite, volcanic arenite, calcarenite, chalk, and phosphorite were also recovered. Bottom photographs reveal rough, cliff-and-terrace topography.

A. Petrography

Felsic and intermediate igneous rocks are much more abundant constituents of the volcaniclastic debris breccia recovered from Area I than olivine basalt. As a general statement, the igneous rock clasts are porphyritic, with phenocryst abundances at ten percent or less. Groundmass textures are commonly intergranular and the rocks vesicular. Pronounced flow structure is characteristic of the extrusive rocks.

Trachyte is hornblende-phyric and also contains augite and sanidine phenocrysts. The several varieties of trachyte range in texture from nearly aphyric to densely porphyritic. Some sparingly phyric types have a spotted or paisanitic texture.

A single clast of dioritic-textured hornblende syenite was recovered. The rock has adhering hornblende-phyric lava. The syenite clast may be a dike fragment related to trachyte volcanism.

The most common hyaloclastite recovered has abundant, easily freed phenocrysts of augite, hornblende, and plagioclase and is probably hawaiitic in composition. Though similar in many of its physical properties to hyaloclastite recovered from other Midpac 2 study areas, it is generally much less altered. Similar hyaloclastite was recovered from Titov Seamount, q.v.

Gradations between hyaloclastite and volcaniclastic debris breccia are common, and indeed, rock of this type is the most abundant in the dredge haul recovery from Area I. Five varieties of breccia contain trachyte clasts. Porosity in the breccia varies greatly and is commonly related to cement type and abundance. The most porous varieties are cemented with phillipsite and the least porous are cemented with apatite. Sorting is generally poor and framework and matrix grains are commonly subangular, less frequently subrounded. Rare, angular pebble-size clasts of moderately well-sorted, stratified, nontronitized volcanic arenite occur in some varieties of breccia.

Phosphatized foraminiferal calcarenite was commonly recovered in dredge hauls from the summit region. One dredge haul contained mostly chalk composed foraminifera and nannoplankton. Some varieties of breccia have this chalk as matrix.

Clasts of phosphorite occur in some varities of breccia. These clasts are autobreccias of phosphatized chalk with small percentages of phosphatized calcareous pellets and altered trachyte fragments.

B. Alteration

The rocks are altered by smectitic argillation, oxidation, phosphatization, zeolitization, amphibolization, recrystallization, and carbonation. The range of alteration is from superficial to complete. Olivine is replaced with iddingsite and augite is variably amphibolized. Feldspars are superficially zeolitized. Phillipsite lines cavities in igneous rocks and open spaces in volcaniclastic rocks. In places, calcite also lines or fills open spaces in the rocks. Most calcareous rocks are phosphatized to varying extents.

C. Lithic distribution

The rough cliff-and-terrace structure of Area I has accumulated extensive and diverse deposits of clastic rocks and biogenic sediments. Hyaloclastite and chalk are perhaps the only primary rocks exposed as outcrops. Olivine basalt was rarely recovered and probably from greater depth than most other rocks in the dredge hauls. Hornblende-bearing lavas of a broad compositional range occur abundantly in most of the dredge hauls, with diversity of types increasing toward the summit of the seamount. Trachyte and phosphorite were recovered from far down the slopes to the summit. Most dredge hauls contained hyaloclastite, but the greatest abundances were in dredge hauls from near the summit. Syenite clasts were recovered from the summit.

III. Discussion

Nine submarine volcanic structures in the central Pacific were surveyed during Midpac 2 and although none were examined with enough detail to decipher the geologic history of the edifices, certain inferences can be made concerning the general geology. Most dredge hauls were done on small sectors of volcanic edifices in water depths of between 1000m and 2000m and thus represent a preferential sampling of the upper flanks and and summit areas. Bottom photographs and detailed Seabeam bathymetry (proprietary German data) of areas much larger than the dredge haul tracks provide insight into the structure of the volcanoes and the distribution of detritus and biogenic sediment on the edifices.

The igneous rocks, their eruptive sequences, and the sedimentary processes inferred for the submarine volcanoes of Midpac 2 are similar to those of both submarine and subaerially-exposed linear volcanic island chains elsewhere in the central Pacific. Most of the Midpac 2 volcanic structures are guyots. Wave action at the volcano summit-ocean interface planed many of the mountaintops before they were ultimately submerged. Many of the summits are now hundreds to thousands of meters underwater. Darwin (1837) explained this phenomenon by proposing a rise in sealevel. Hamilton (1956) proposed that oceanic crustal subsidence was a more reasonable explanation. Midpac 2 dredge haul samples include numerous deeply-weathered, subrounded clasts of highly vesicular, subaerially-erupted flow lavas intermingled with abundant subangular clasts of lavas of the same composition in volcaniclastic debris breccia. Clasts of phosphatized calcareous reef and lagoonal deposits are also common components of the breccia. Such assemblages characterize the Midpac 2 dredge hauls from the upper slopes and summits of the seamounts and similar clastic assemblages are found at the same general location on submarine volcanic edifices throughout the central Pacific (Schlanger et al., 1984). These volcanic edifices vary in age and demonstrate that slow oceanic crustal subsidence is the cause of seamount submergence because of the common occurrence of subaerially-weathered rock clasts mingled with unweathered angular rock clasts fragmented by submarine tectonic processes and incorporated into debris flows. The frequent intermingling with these rock clasts of phosphatized calcareous lagoonal and reef rock debris further supports the principle of inundation by subsidence. Reefs have built up slowly and continuously over many millions of years on the summits of the guyots as the volcanic edifices slowly subsided (Haggerty et al., 1982), (Schlanger et al., 1984).

Midpac 2 region volcanism is similar to that of the Hawaiian Islands-Emperor Seamounts Chain. Macdonald (1968) explained the igneous petrology and construction of Hawaiian volcanoes based on the eruption of lavas of distinctive compositions in a four-stage sequence: (1) tholeiitic shield basalt,(2) tholeiitic and alkalic caldera-filling basalt, (3) post-caldera-filling alkalic basalts and differentiated lavas, and (4) post-erosional subsilicic alkalic basalts. Recent studies by Moore et al.(1982) indicate a modification of this sequence in which eruption of subsilicic alkalic basalt also precedes eruption of tholeiitic shield basalt. This phenomenon occurs at Loihi Seamount, which is thought to be the vanguard of the Hawaiian Ridge "hot spot" volcanism. Volcanic rocks and eruptive sequences similar to those of Macdonald's model occur in the Line Islands (Bass et al., 1973) and in distant linear island "hot spot" chains such as the Caroline Islands in the western Pacific (Keating et al., 1984). Igneous rocks recovered on Midpac 2 resemble those of the post-caldera and post-erosional stages of Macdonald's model, or to the "post-shield" and "rejuvenated" stages proposed by Clague and Dalrymple (1987). The assignment of the Midpac 2 igneous rocks to these stages is based on the abundance of felsic and basaltic rocks with alkali-bearing mineral phases such as nepheline, analcime, kaersutite, and aegirine in the dredge haul recovery from the summits and upper slopes of the submarine volcanic edifices of this region. The apparent eruptive sequence of the Midpac 2 igneous rocks is: (1) alkali olivine basalt, (2) trachyte and differentiated alkalic lavas, and (3) subsilicic alkalic lavas. Good examples of this inferred sequence are seen in Areas E and I. In Area E, the igneous rocks immediately beneath the broad summit of the guyot are alkali olivine basalt flows and pyroclastic rocks. Isolated outcrops of trachyte occur near the southern edge of the summit. Differentiated alkalic lavas are abundant in dredge hauls made on volcanic structures surmounting the main summit of the guyot. In Area I, located on the summit and slopes of a pinnacle-like volcanic structure surmounting a large, arcuate ridge, alkali olivine basalt appears to be the basement igneous rock which is surmounted by differentiated alkalic lavas, trachyte, and subsilicic alkalic lavas. The rocks become progressively more felsic toward the summit.

The Hawaiian Islands-Emperor Seamounts Chain is a linear progression of volcanic edifices subsiding with increasing age from a fixed source of active volcanism which has its origin in the earth's upper mantle (Dalrymple et al., 1980). In the Line Islands, no such regular age progression is observed, in spite of the the linear disposition of volcanic edifices in the archipelago. Recent studies in micropaleontology (Haggerty et al., 1982), and in geochronology and paleomagnetics (Schlanger et al., 1984) show many inconsistensies in the age and magnetic signature of the volcanic edifices throughout the length of the archipelago from the Tuamotu Islands to the southeast to Johnston Island in the northwest. The Mid-Pacific Mountains display an equally complex history. The submarine geology of the Phoenix Islands is little known, but igneous rocks recoveron Midpac 2 from Titov Seamount in that area are petrologically similar to those from linear island chains elsewhere in the central Pacific. Observations of the volcanic edifices of Midpac 2 are consistent with the observations made in 1984 by Schlanger et al. Forthcoming investigations of the Midpac 2 rock samples should add important new information for the interpretation of the geology of this remote region and help unravel its complex history and origin.

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V. References

Bass, M. N., Moberly, R., Rhodes, J.M., and Church, S.E., 1973. Volcanic rocks cored in the central Pacific, DSDP Leg 17. In: Winterer, E. L., Ewing, J. I., et. al., Initial Reports of the Deep Sea Drilling Project 17:429-466, Washington, D. C. (U. S. Gov't Printing Office).

Carlisle, D., 1963. Pillow breccias and their aquagene tuff in Quadra Island, British Columbia. J. Geol. 71:48-71.

Clague, D. A., and Dalrymple, G. B., 1987. The Hawaiian-Emperor volcanic chain, part I, geologic evolution. In: Decker, R. W., Wright, T. L., and Stauffer, P. H., eds. Volcanism in Hawaii: U. S. Geol. Surv. Prof. Paper 1350, Washington, D. C. (U. S. Gov't Printing Office) I:5-56.

Clague, D. A., and Friesen, W. B.,(in preparation). Mineralogy and petrology of volcanic rocks from Niihau Island, Hawaii. U. S. Geol. Surv. Open-file Report.

Dalrymple, G. B., Lanphere, M. A., and Clague, D. A., 1980. Conventional and 40 AR/39K-Ar ages of volcanic rocks from Ojin (Site 430), Nintoku (Site 432), and Suiko (Site 433) Seamounts and the chronology of volcanic propagation along the Hawaiian-Emperor Chain. In: Jackson, E. D., Koizumi, I., et. al., Initial reports of the Deep Sea Drilling project 55:659-676, Washington, D. C. (U. S. Gov't Printing Office).

Darwin, C., 1837. On certain areas of elevation and subsidence in the Pacific and Indian Oceans, as deduced from the study of coral formations. Proceedings of the Geological Society of London 2:552-554.

Dymond, J., and Windom, J. L., 1968. Cretaceous K-Ar ages from Pacific Ocean seamounts. Earth and Planetary Sci. Let. 4:47-52.

Haggerty, J. A., Schlanger, S. O., and Premoli-Silva, I., 1982. Late Cretaceous and Eocene volcanism in the southern Line Islands and implications for hot spot theory. Geology 10:427-433.

Hamilton, E. L., 1956. Sunken islands of the Mid-Pacific Mountains. Geological Society of America Memoir 64.

Jackson, E. D., Bargar, K. E., Fabbi, B. P., and Heropoulos, C., 1976. Petrology of basaltic rocks drilled on Leg 33 of the Deep Sea Drilling Project. In: Schlanger, S. O., Jackson, E. D., et. al., Initial Reports of the Deep Sea Drilling Project 33:517-630, Washington, D. C.(U. S. Gov't Printing Office).

Jackson, E. D., Koizumi, I., Dalrymple, G. B., Clague, D. A., Kirkpatrick, R. J., and Greene, H. G., 1980. Introduction and summary of results from DSDP Leg 55, the Hawaiian-Emperor hot spot experiment. In: Jackson, E. D., Koizumi, I., et. al., Initial Reports of the Deep Sea Drilling Project 55:5-31, Washington, D. C. (U. S. Gov't Printing Office).

Keating, B. H., Mattey, D. P., Helsley, C. E., Naughton, J. J., Epp, D., Lazarewicz, A., and Schwank, D., 1984. Evidence for a hot spot origin for the Caroline Islands. J. of Geophys. Res. 89:9937-9949.

Kirkpatrick, R. J., Clague, D. A., and Friesen, W. B., 1980. Petrology and geochemistry of volcanic rocks, DSDP Leg 55. In: Jackson, E. D., Koizumi, I., et. al., Initial Reports of the Deep Sea Drilling Project 55:509-557, Washington, D. C. (U. S. Gov't Printing Office).

Macdonald, G. A., 1968. Composition and origin of Hawaiian lavas. In: Coats, R. E., Hay, R. L., and Anderson, C. A., eds., Studies in volcanology. Geol. Soc. Am. Memoir 116:477-522.

Macdonald, G. A., and Katsura, T., 1962. Relationship of petrographic suites in Hawaii. In: Crust of the Pacific Basin. Geophysical Monograph 6:187-195.

Manheim, F. T., and Gulbrandsen, R. A., 1979. Marine Phosphorites. In: Burns, R. G., ed., Marine minerals, Min. Soc. of America short course notes 6:151-173.

Menard, H. W., and Chase, T. E (Compilers), 1971. Bathymetric atlas of the North Pacific Ocean. U. S. Naval Oceanographic Office Pub. No. 1301-02-03, Washington, D. C.

Moore, J. G., Clague, D. A., and Normark, W. R., 1982. Diverse basalt types from Loihi Seamount, Hawaii. Geology 10:88-92.

Natland, J. H., 1975. Petrologic studies of linear island chains (Ph. D. diss.) 384 p.

Natland, J. H., 1976. Petrology of volcanic rocks dredged from seamounts in the Line Islands. In: Schlanger, S. O., Jackson, E. D., et. al., Initial Reports of the Deep Sea Drilling Project 33:749-787, Washington, D. C. (U. S. Gov't Printing Office).

Schlanger, S. O., Garcia, M. O., Keating, B. H., Naughton, J. J., Sager, W. W., Haggerty, J. A., Philpotts, J. A., and Duncan, R. A., 1984. Geology and geochronology of the Line Islands. J. of Geophys. Res. 89:11261-11272.