Petrology of the Basalt Cores From Midway Atoll

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By GORDON A. MACDONALD

GEOLOGY OF THE MIDWAY AREA, HAWAIIAN ISLANDS

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Descriptions of altered basalt lava flows from beneath the reef cap

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PETROLOGY OF THE BASALT CORES FROM MIDWAY ATOLL

By Gordon A. Macdonald

ABSTRACT

Below 1,261 feet in the Reef hole and 516 feet in the Sand Island hole the Midway cores are entirely of greenish-gray altered basalt lava flows that contain a few reddish- or yellowish-brown weathered zones. Both aa and pahoehoe flow types are present, and the vesicularity and other structures are the same as those in Hawaiian subaerial flows. No pillow lavas, hyaloclastite, or tuff are present. Vesicles commonly are filled with clay, chlorite, and serpentine, and less commonly with calcite and zeolite, but many remain open. Soil zones occur between lavas at depths of 1,316 and 1,334 feet in the Reef hole. Olivine is altered to iddingsite and serpentine. Feldspar ranges from labradorite to andesine in composition and is partly altered to clay minerals, particularly in the upper part of the section. Pyroxene is generally fresh, but may be altered to serpentine; it is predominantly augite, but some grains have a small optic axial angle. The lava flows are believed to have been subaerial, but the alteration is believed to be the result of long exposure to sea water. The volcanic cone must have sunk more than 1,260 feet relative to sea level since the flows were formed. Two analyzed specimens are tholeiitic basalt, but the original nature of most of the altered lava flows in the cores is uncertain. However, pebbles from the gravels that overlie the lava flows include alkalic basalt and mugearite, indicating that the Midway volcano had entered the late, alkalic stage.

INTRODUCTION

For many years, geologists have postulated that the low limestone islands of the mid-Pacific rest on submerged volcanic peaks. Two decades ago, seismological studies began to confirm this hypothesis. Finally, it was incontrovertibly proven, for one island at least, when a drill hole on Eniwetok Atoll penetrated the sedimentary cap and entered basalt beneath (Ladd and others, 1953). During the summer of 1965 two holes drilled on Midway atoll also penetrated the sedimentary rocks and entered underlying basalts (Ladd and others, 1967), thus providing a second definitely proven example. The drilling was carried out by the Hawaii Institute of Geophysics, University of Hawaii, supported by the National Science Foundation (grant No. GP4728), in cooperation with the U.S. Geological Survey and the Office of Naval Research.

Midway is one of the Leeward Islands of the Hawaiian chain. Its location is shown in figure 1. The locations of the two drill holes are described by Ladd, Tracey, and Gross (1969) and are shown in figure 2. The hole drilled on the reef is known as the Reef hole, and that on Sand Island as the Sand Island hole.

Below 1,261 feet in the Reef hole and 516 feet in the Sand Island hole, the Midway cores are entirely of altered basalt lava flows. The basalts are overlain by detrital sedimentary rocks that contain much fragmental volcanic material. In the Reef hole, about 1 foot of basalt conglomerate rests on the upper surface of the lava flows; in the Sand Island hole 9 feet of material that directly overlies the lava flows consists of loose fragments of highly weathered basalt and is apparently regolith.

The lava cores have been examined both megascopically and microscopically in the laboratories of the Institute of Geophysics, University of Hawaii. Through the kindness of D. M. McGuire, of the Institute of Geophysics, I have also been able to examine thin sections of the volcanic pebbles from the sediments above the lavas. Only a few brief comments on the pebbles are given here because the detrital sediments are being studied in detail by McGuire and Ralph Moberly, Jr., University of Hawaii.

In studying the lava cores, two main concerns have been whether the flows were subaerial or submarine and whether the rocks are tholeiitic or alkalic. If the flows were erupted subaerially or in very shallow water their present position indicates that the volcanic mass has sunk relative to sea level. This confirms the general hypothesis of subsidence of the volcanic mountains in the mid-Pacific and adds to the evidence of subsidence found in the sedimentary rocks.

In the major islands of the Hawaiian chain, the greater part of the shield volcanoes consists of tholeiitic rocks, which are overlain by relatively small volumes of alkalic rocks (Powers, 1955; Kuno and others, 1957; Macdonald and Katsura, 1964). The same sequence is

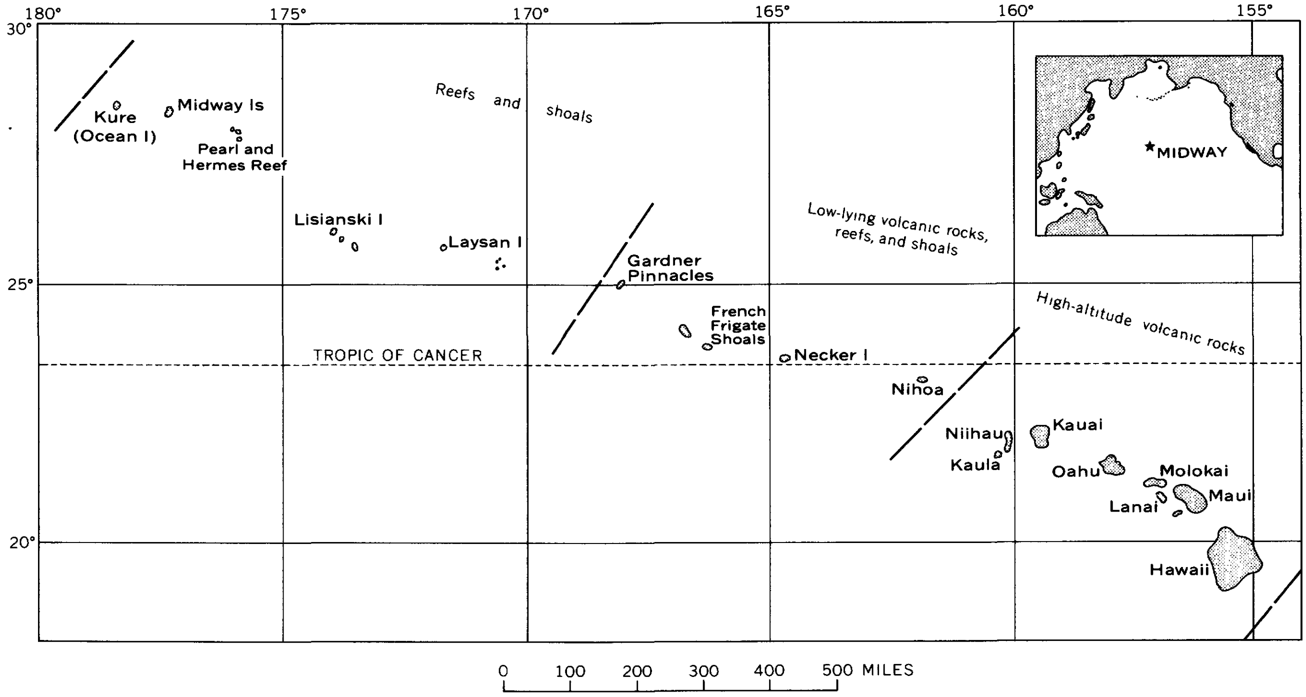


Figure 1.—The Hawaiian chain, showing the three major physiographic subdivisions (bounded by dashed lines). From Ladd, Tracey, and Gross (1969).

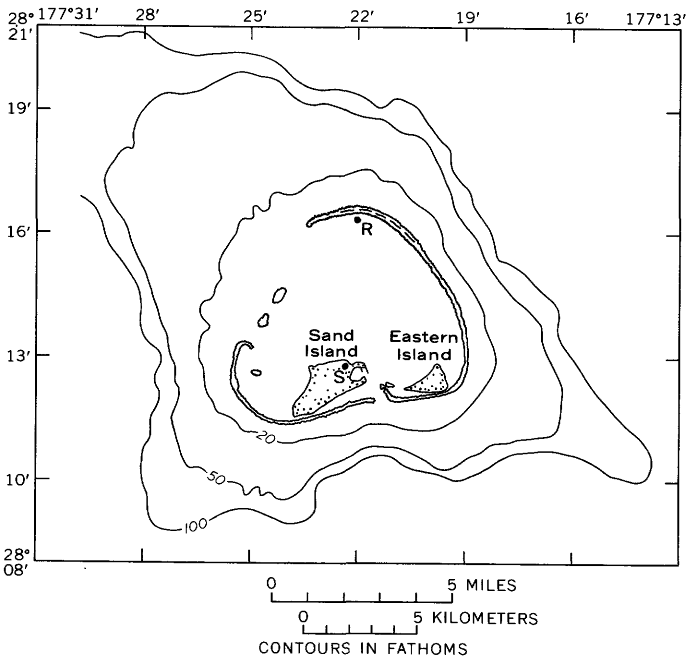


Figure 2.—Midway atoll, showing the location of the Reef (R) and Sand Island (S) drill holes.

presumed to be present in other mid-Pacific islands, but this has not actually been demonstrated. In the Galaposos Islands, the active shield volcanoes are erupting tholeiitic lavas, whereas the older volcanoes consist of alkalic rocks (Williams, 1965), but tholeiitic rocks have not yet been found underlying alkalic rocks in the same volcano. Tholeiitic rocks have not been identified in any other volcanic island of the Pacific, though they may be present in the submerged parts of the volcanoes (Macdonald, 1968a), and they seem to be widespread on the deep ocean floor (Engel and others, 1965). In the Indian Ocean, rocks transitional between tholeiitic and alkalic types have been found beneath typical alkalic rocks in the dissected volcano, Piton des Neiges, on Réunion Island (Upton and Wadsworth, 1966). In the Atlantic Ocean, tholeiitic rocks have been dredged from the lower slopes of the Mid-Atlantic Ridge (Engel and Engel, 1964), though lavas in the parts of the ridge that is above sea level are alkalic. The finding of tholeiitic basalts overlain by alkalic rocks in Midway extends the known distribution of tholeiitic rocks in the Hawaiian Ridge, in both time and space, and strengthens the general petrologic hypothesis stated above.

MEGASCOPIC FEATURES

The basaltic lava flows in the Midway cores range from medium to dark greenish gray and contain a few reddish- or yellowish-brown zones. Altered phenocrysts of olivine are recognizable in most samples, and in some they composed as much as 20 percent of the rock. Megascopically, most of the rocks more closely resemble typical tholeiitic lavas than alkalic lavas of the major Hawaiian Islands.

Both pahoehoe and aa flows are present. The central parts of aa flows are massive and dense, and core recovery from them was nearly 100 percent. Core recovery from clinker parts of aa flows was much less. The clinker fragments are generally more highly altered than the massive parts of the flows and commonly are soft enough to be crushed between one's fingers. Spaces between the fragments that were originally open have been partly or completely filled with secondary material—clay, chlorite, serpentine, and, less commonly, calcite and zeolite.

Pahoehoe flows range from moderately to highly vesicular. The vesicles usually are partly or wholly filled with serpentine and chlorite or, more rarely, with calcite and zeolite, but in some zones even at the deepest levels the vesicles remain mostly open.

Zones of brown and red soil are present in the Reef hole between 1,316 and 1,318 feet and between 1,334 and 1,336 feet. Between 1,309 and 1,311 feet, the vesicular basalt and clinker are stained by red oxides, which probably formed during subaerial weathering. Between 1,633.0 and 1,633.6 feet the basalt is altered to red clay, in which slickensided shear surfaces bear flecks of metallic copper. The underlying 1.5 feet of basalt is somewhat reddened.

Detailed logs of the cores are given in table 1, and the general relationships of the rocks are shown in figure 3.

No pillow structures were found in the Midway cores; there was neither any hyaloclastite, resulting from granulation of the hot lava in contact with water, nor tuff, resulting from explosions caused by hot lava coming in contact with water. The vesicularity of the rocks covers the same range as that found in lavas erupted above sea level in the Hawaiian and Samoan Islands. As at Sylvania Seamount and Eniwetok (Macdonald, 1954, 1963), the lavas probably were not erupted far below sea level, and they very likely were erupted above sea level. This conclusion is supported by Moore's (1965) findings on the submerged slopes of Hawaiian volcanoes, where the abundance and size of vesicles in the lavas decrease with increasing depth of water until at depths greater than 12,000 feet the rocks are essentially devoid of visible vesicles. The theory that the Midway flows are of subaerial origin is supported by the presence of soil zones and reddened oxidized zones that could not have been formed below sea level. The conclusion is inescapable that the lavas now at depths as great as 1,654 feet below sea level at Midway were erupted near or above sea level.

MICROSCOPIC FEATURES

Thin sections were cut from all the fresher appearing parts of the lava flows in the cores. The friable highly decomposed parts were not sectioned. Twenty-six thin sections of lava flows from the Reef hole and four from the Sand Island hole were examined under the microscope. In addition, about 100 thin sections of pebbles from the sediments above the lava flows were scanned, and 18 studied in detail.

Feldspar compositions were determined mostly by extinction-angle methods, these were checked occasionally by optic axial angle and sign, and, in a few samples, by refractive index determined in immersion liquids. The optic axial angle in pyroxenes and feldspars was estimated from the optic axis or nearly centered acute bisectrix interference figures.

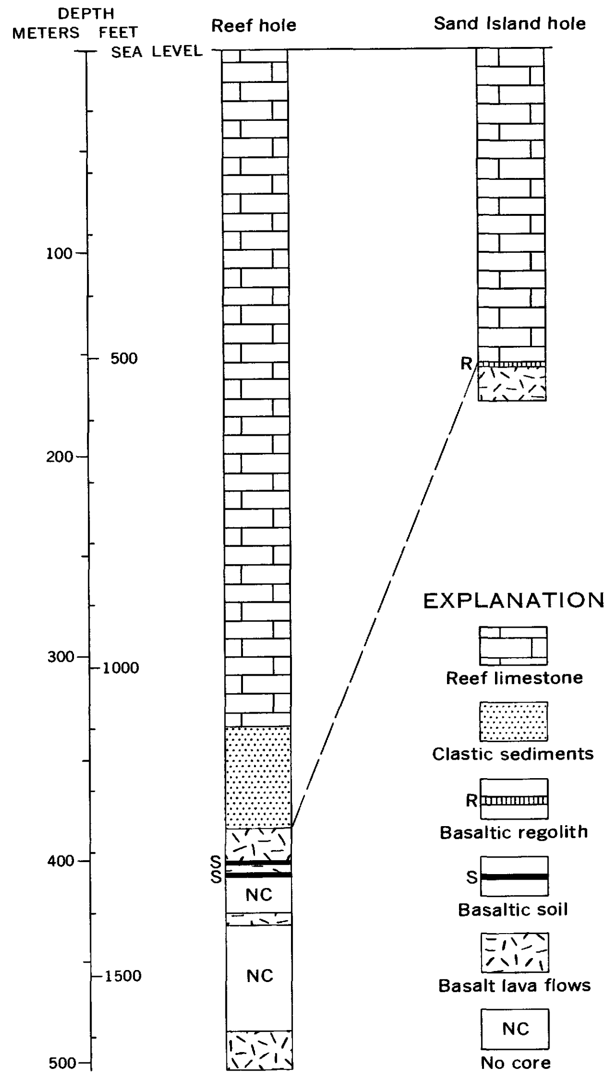


FIGURE 3.—Logs of the two Midway drill holes, showing the basaltic parts of the cores and zones of soil and regolith in relation to the sedimentary rocks. Parts marked no core are those in which a rock bit was used instead of a core bit.

TABLE 1.—*Logs of basalt cores from the two drill holes on Midway*

Depth (ft)	Description
Reef hole	
0-1096	Reef limestones.
1096-1260	Sedimentary materials.
1260-1261	Basalt conglomerate.
1261-1266	Partly altered, moderately vesicular to dense, olivine basalt.
1266-1270	Similar to above but more altered; contains clinkery zones at 1266-1267 and 1269.7-1270 ft. At 1267.5-1268 ft, a former cavity is filled with brown clay.
1270-1271.4	Clinkery olivine basalt, like above.
1271.4-1273.3	Moderately vesicular, partly altered basalt.
1273.3-1275	Clinkery basalt, altered.
1275-1277	Same as above; cavities partly filled with clay.
1277-1281.2	Moderately vesicular pahoehoe basalt, partly altered.
1281.2-1285	Clinkery basalt; cavities partly filled with calcite and zeolite.
1285-1286.5	Moderately vesicular basalt, much altered.
1286.5-1290	Clinkery basalt, much altered; bottom 2 in. reddened.
1290-1293	Much altered clinkery basalt.
1293-1295	Moderately to highly vesicular pahoehoe basalt, partly altered.
1295-1295.7	Sparingly vesicular, partly decomposed basalt.
1295.7-1299	Moderately vesicular basalt that contains scattered phenocrysts of olivine, highly altered.
1299-1302	Sparingly vesicular basalt; less altered than above; many vesicles filled with calcite and zeolite(?).
1302-1304	Moderately vesicular altered basalt.
1304-1308.5	Sparingly vesicular altered basalt.
1308.5-1309.5	No core.
1309.5-1310	Sparingly to moderately vesicular altered basalt, slightly reddened.
1310-1310.7	Clinkery basalt, reddened and much decomposed.
1310.7-1313.5	Clinkery basalt, decomposed, reddened at top.
1313.5-1315.7	Moderately vesicular olivine basalt, decomposed.
1315.7-1316.3	No core.
1316.3-1317.7	Brown soil.
1317.7-1318.1	Red soil.
1318.1-1321.3	Much decomposed, gray to brown or red, basalt clinker(?).
1321.3-1326.3	Same as above; resembles subsoil.
1326.3-1334.4	Same as above.
1334.4-1336.3	Basaltic soil, reddened at top.
1336.3-1398.5	No core.
1398.5-1413.5	Moderately to sparingly vesicular olivine basalt, moderately decomposed.
1413.5-1418.5	Same as above, but middle 2 ft somewhat clinkery.
1418.5-1591	No core.
1591-1597.2	Moderately to sparingly vesicular basalt, moderately decomposed.
1597.2-1599.3	Clinkery basalt.
1599.3-1606	Moderately vesicular basalt, slightly decomposed.
1606-1611	Alternating dense and vesicular basalt, moderately decomposed.
1611-1616	No core.
1616-1618	Clinkery basalt, reddened.
1618-1633	Sparingly vesicular to dense basalt, somewhat decomposed.
1633-1633.6	Basalt altered to red clay; flec..s of metallic copper on slickensided shear surfaces.
1633.6-1635	Somewhat reddened altered basalt.
1635-1636	Sparingly vesicular basalt that contains abundant altered phenocrysts of olivine.
1636-1641	Moderately to highly vesicular basalt pahoehoe; many altered phenocrysts of olivine.
1641-1646	Same as above, but a zone from 1641.7 to 1642.8 ft contains abundant vesicles filled with secondary minerals, whereas in the rest of this interval the vesicles are mostly open.
1646-1649.5	Sparingly vesicular basalt, locally clinkery; contains only scattered phenocrysts of altered olivine.
1649.5-1652	Reddened altered basalt.
1652-1654	Sparingly vesicular basalt, locally clinkery.
Sand Island hole	
0-501	Reef limestones.
501-503.2	Brownish-green clay, calcareous; contains shell fragments.
503.2-504.5	Like above, but darker brown and without shell fragments.
504.5-506.8	Like above, but greener and contains fragments o. dark-brown rotted vesicular basalt.
506.8-507	One fragment of partly altered dense basalt.
507-516	Loose fragments of much weathered basalt.
Sand Island hole—Continued	
516-520.3	Core mostly lost. About 0.8 ft of material like above.
520.3-525	Much altered, moderately vesicular olivine basalt; vesicles are largely filled with secondary miner ıls.
525-530	Much altered olivine basalt containing altered phenocrysts of olivine; patches of bright green secondary material in a dark clay matrix between 529 and 530 ft.
530-534.4	Moderately vesicular basalt, thoroughly altered, though somewhat less so than the rock between 525 and 530 ft; vesicles are partly filled with yellowish-green clay.
534.4-538	No core.
538-541.6	Altered olivine basalt; the bottom 6 in. less altered than the rest; resembles the rock between 530 and 534.4 ft.
541.6-558	A few fragments of altered vesicular basalt, from core catcher.
558-564	Moderately vesicular basalt; vesicles are filled with secondary chlorite, and abundant olivine phenocrysts are altered to serpentine; some vesicles and fractures are filled with white calcite and zeolite(?).
564-567	Moderately vesicular, slightly porphyritic, altered basalt.
567-568	Dense, somewhat altered basalt.

All samples of the lava flows examined under the microscope are very similar. All are olivine basalts, and the chief variation is in the abundance of olivine phenocrysts. The phenocrysts are as much as 5 mm long, but most are less than 1 mm long; they grade in size into the groundmass. Many are rounded and embayed as a result of resorption, but others remain sharply euhedral. Skeletal crystallization is fairly common. The larger phenocrysts are altered around the edges to iddingsite, or less commonly to goethite(?), and in the center to serpentine (antigorite?). The microphenocrysts and olivine grains of the groundmass commonly are altered throughout to iddingsite. Thin rims of serpentine surround the iddingsite on a few of the phenocrysts and apparently represent a second generation of olivine deposited after the alteration of the outer part of the phenocryst to iddingsite. Similar rims of late-formed olivine are common in Hawaiian olivine basalts. In those rocks the iddingsite is believed to have formed just before and during eruption, when gases were concentrated in the magma, and, additional olivine was precipitated during crystallization of the groundmass after eruption (Macdonald, 1949, p. 1545). Olivine in the Midway lava flows is completely altered, but in some pebbles in the overlying gravels part of the olivine remains unaltered. In one such pebble, the texture resembles that of the lava flows, and the olivine has $+2V \approx 85°$.

Small phenocrysts and microphenocrysts of augite ($+2V=55°-60°$) are present in a few rocks but are not common; feldspar phenocrysts more than 0.3 mm long are even rarer. Both grade in size into the groundmass. The groundmass is generally intersertal, less commonly intergranular, and is composed of plagioclase, altered olivine, monoclinic pyroxene, magnetite, ilmenite, and usually interstitial serpentine. The serpentine probably is an alteration product of original interstitial glass. Plagioclase ranges from intermediate labradorite to calcic or intermediate andesine. Most grains are subhedral, and many show normal zoning. Some anhedral interstitial grains are present, and these commonly are andesine. No alkalic feldspar or silica minerals were recognized.

In some rocks, particularly in the upper part of the section, the feldspar is partly altered to clay minerals. The groundmass olivine may be completely altered to a reddish-brown substance that resembles iddingsite but is probably a mixture of goethite and clay minerals or is altered partly to this mixture and partly to serpentine. Rarely, the olivine has altered completely to serpentine. No fresh olivine or fresh glass was found in any of the lava flows. Both the serpentine which replaces olivine and the interstitial serpentine appear to be antigorite.

Most large grains of groundmass pyroxene are augite ($+2V=50°–60°$), but in a few specimens some grains have an optic axial angle near 0°. In other rocks some small grains also appear to have a small 2V, but good interference figures could not be obtained on them. Whether these small grains are augite or pigeonite remains in doubt. No orthorhombic pyroxene was found. The pyroxene usually appears to be completely fresh, but in a few slides it is slightly altered to what is apparently very fine grained serpentine.

The vesicles are partly or completely filled with fibrous secondary minerals, which commonly show concentric banding. In some vesicles the material seems to be antigoritic serpentine throughout, but more commonly a band of serpentine ($\gamma - \alpha \approx 0.005$) is succeeded inward by a mineral that has a higher birefringence (≈ 0.009), perhaps a chlorite. Fibers of both minerals show positive elongation. Some vesicles have a very thin outer band of isotropic serpophite, within which are the bands of serpentine and chlorite(?). No quartz and very little zeolite and calcite were recognized in the vesicles of the lava flows, though zeolite and calcite are commonly present in pebbles in the overlying gravels.

Skeletal development of olivine phenocrysts and continuation of crystallization of olivine into the groundmass generation are characteristic of alkalic olivine basalts; however, though far less common, these features are also found in tholeiitic olivine basalts. Resorption of olivine phenocrysts is characteristic of tholeiitic basalts, though it has also been found in some alkalic basalts (Macdonald and Katsura, 1964, p. 91). Groundmass pigeonite is characteristic of tholeiitic basalts, but augite also is common, particularly among the large grains. However, clinopyroxene that has a small 2V also occurs in alkalic basalts (though it may be an augite rich in ferric iron rather than a true pigeonite), so that the occurrence of pyroxene with small 2V is not in itself wholly diagnostic of tholeiitic basalt (Macdonald and Katsura, 1964, p. 90). Interstitial feldspar more sodic than labradorite is characteristic of alkalic basalts but is found also in tholeiitic basalts (Wentworth and Winchell, 1947, p. 66). Thus, the microscopic criteria are not wholly adequate to identify the lava flows in the Midway cores as definitely tholeiitic or alkalic.

Among the pebbles in the overlying sedimentary section, several are composed largely of tiny acicular microlites of oligoclase or andesine arranged in the very pronounced flow pattern that is characteristic of mugearites and hawaiites. Two pebbles contain large flakes of brown biotite, and one contains large grains of dark apatite similar to those observed in several samples of mugearite from the major Hawaiian Islands and in similar lavas of Mount Etna, Sicily. These pebbles are unmistakably mugearites. The texture of other pebbles that contain abundant tiny grains of olivine in the groundmass very closely resembles that of typical alkalic olivine basalts. The presence of the mugearites definitely indicates that the upper part of the Midway volcano contained alkalic lavas.

Except in the soil zones and reddened oxidized zones that probably resulted from normal subaerial weathering, the alteration of the Midway rocks differs from any alteration found in rocks of the major Hawaiian Islands. Serpentinization, even of olivine, is very rare in weathered subaerial lavas in Hawaii, where the serpentinization of glass and filling of vesicles with serpentine are unknown. Alteration of lavas in the caldera areas of the Koolau volcano, Oahu, and the East Molokai volcano superficially resembles the alteration of the Midway rocks but differs markedly from it in detail. Whereas the pyroxene in the Midway rocks is almost unaltered, that in the caldera rocks, altered by rising volcanic gases, has been almost wholly converted to chlorite. Olivine in the caldera rocks has been altered to chlorite, not to serpentine as at Midway. Epidote is fairly common in the caldera rocks, and silica released by the alteration of pyroxene to chlorite has been redeposited as quartz and chalcedony in veinlets and amygdules; but no epidote and free silica have been found in the Midway rocks. The alteration of the Midway rocks apparently took place under conditions different from those affecting the subaerial lavas of the major Hawaiian Islands and probably resulted from long saturation of the rocks with sea water.

351-473 O—69——2

CHEMICAL ANALYSES

Most Midway lavas are so altered that chemical analyses are of little value in determining the original composition of the rocks. Analyses of two of the least altered parts of the cores, from depths of 1,401.3 and 1,600.2 feet in the Reef hole, r, are given in tables 2 and 3. It is immediately obvious from the large water content and the high degree of iron oxidation that even these samples are considerably altered; the sample from 1,401 feet is more altered than the deeper sample. CIPW norms calculated from the analyses also are given in table 2. Both norms contain excess silica, which suggests that the rocks are tholeiitic. The high degree of iron oxidation greatly increases the amount of free silica in the norm, however, and even markedly alkalic rocks, if they are highly oxidized, may show quartz in the norm.

To minimize the effects of alteration on the norm, the analyses have been recalculated (1b and 2b, table 2) water free and with the Fe_2O_3/FeO ratio reduced to 0.2, which is the average ratio found in fresh Hawaiian tholeiitic basalts. The average Fe_2O_3/FeO ratio is higher in alkalic rocks than in tholeiitic rocks, but assumption of the lower ratio has the greatest possible effect in reducing the amount of quartz in the norm and, in this respect, reducing the tholeiitic aspect of the norm. Note that even with this extreme assumption the recalculated norms (table 2) still contain quartz and abundant hypersthene. Thus the norms of the recalculated analyses are also decidedly tholeiitic.

Some leaching of the alkalies, particularly sodium, probably occurred during alteration of the rocks, but there does not seem to be an adequate way of estimating the exact amount. Although potassium also has no doubt been liberated during alteration of the feldspars, most has probably been retained in the secondary alteration minerals, and the amount of potassium in the total rock may remain little changed. The potassium content of the Midway basalts is within the normal range for Hawaiian tholeiites, but it is decidedly lower than that for Hawaiian alkalic rocks (fig. 4). In the less altered specimen, from the 1,600-foot depth, the sodium content is within the normal range for Hawaiian tholeiites but much below that for the alkalic rocks (fig. 4).

Titanium oxide content is somewhat higher than that in most Hawaiian tholeiites but falls within the range found in those rocks (fig. 4); it is near the average for alkalic basalts (Macdonald, 1968b). Titania content of tholeiitic basalts varies considerably from one volcano to another, and that of the fresher Midway sample (1b, table 2) is nearly the same as the average for Kilauea volcano (Macdonald and Katsura, 1964, table 9, p. 124). Thus, although the titania content in the Midway samples favors an alkalic interpretation for these basalts, it is indeterminate.

TABLE 2.—*Chemical analyses and CIPW norms of Midway basalts*

[Results in weight percent. Analyst: Vertie C. Smith]

	1a	2a	1b	2b
Major oxides				
SiO_2	46.21	41.79	48.9	48.0
Al_2O_3	14.67	12.78	15.6	14.8
Fe_2O_3	7.36	10.72	2.1	2.3
FeO	5.04	2.32	10.4	11.5
MgO	5.96	8.98	6.3	10.3
CaO	9.52	6.63	10.1	7.6
Na_2O	2.38	1.29	2.5	1.5
K_2O	.36	.25	.4	.3
H_2O+	1.52	3.83		
H_2O-	3.39	7.78		
TiO_2	2.78	2.63	2.9	3.0
P_2O_5	.26	.23	.3	.3
MnO	.18	.16	.2	.2
CO_2	.04	.05		
Cl	.24	.15	.3	.2
F	.03	.02		
Subtotal	99.94	99.61		
Less O	.07	.04		
Total	99.87	99.57	100.0	100.0
CIPW norms				
Q	6.24	6.96	.8	1.3
or	2.22	1.67	2.2	1.7
ab	19.91	11.00	21.0	12.6
an	28.36	28.08	30.3	32.8
di:				
wo	7.08	1.16	7.4	1.3
en	6.10	1.00	4.0	.8
fs			3.2	.4
hy:				
en	8.80	21.40	11.8	25.0
fs			9.8	14.3
mt	8.82	.23	3.0	3.2
hm	1.28	10.56		
il	5.32	5.02	5.5	5.8
ap	.67	.67	.7	.7

1a. Basalt from 1,600.2 ft in the Reef hole.
2a. Basalt from 1,401.3 ft in the Reef hole.
1b. Sample 1a recalculated to 100 percent, water free and with Fe_2O_3/FeO ratio reduced to 0.2.
2b. Sample 2a recalculated in same way as sample 1b.

TABLE 3.—*Abundance of minor elements in Midway basalts*

[Sample 1 is from 1,600.2-foot depth, and sample 2 is from 1,401.3-foot depth, in the Reef hole—the same as those in table 2. Results are in parts per million. Analyst: R. H. Heidel. Elements looked for but not detected: Ag, As, Au, Be, Bi, Cd, Ce, Ge, Hf, Hg, In, La, Li, Mo, Pb, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. Nb is present, but below the limit of measurement]

	1	2		1	2
B	(1)	50	Sc	30	30
Ba	70	20	Sr	300	100
Co	70	70	V	500	200
Cr	150	700	Y	50	50
Cu	150	150	Yb	<5	<3
Ga	<30	<30	Zr	150	100
Ni	100	300			

[1] Looked for but not detected.

The strontium and zirconium contents of the Midway rocks are much lower than the normal range for alkalic basalts but are well within the range observed for tholeiitic basalts (fig. 4). Indeed, the zirconium content is low even for the tholeiitic rocks; in Hawaiian soils produced by subaerial weathering, however, sufficient zirconium is usually retained to serve as a good indication that the soils were derived from alkalic basalt (Kimura and Swindale, 1967). The abundance of copper is similar to that in Hawaiian tholeiitic basalts but much greater than that normally found in alkalic basalts or related alkalic rocks (fig. 4).

Thus, most data from the chemical analyses indicate quite definitely that the samples analyzed are tholeiitic.

CONCLUSIONS

In the cores from Midway atoll, altered basalt lava flows occur beneath the sedimentary caprock. The lower part of the basalt section contains tholeiitic olivine basalt. Alkalic olivine basalts may be associated with the tholeiites higher in the basalt section, and mugearites definitely are present, as indicated by pebbles of this composition in the overlying sedimentary rocks. The lava flows are ordinary pahoehoe and aa, have the normal vesicularity of subaerial flows, and were erupted above sea level or in very shallow water. If the lavas were erupted in shallow water, they were at times elevated above sea level for periods long enough to permit the formation of soil on them by subaerial weathering. The present position of the lavas must have resulted from subsidence of the volcanic mountain. The pervasive alteration of the rocks is the result of long saturation by sea water.

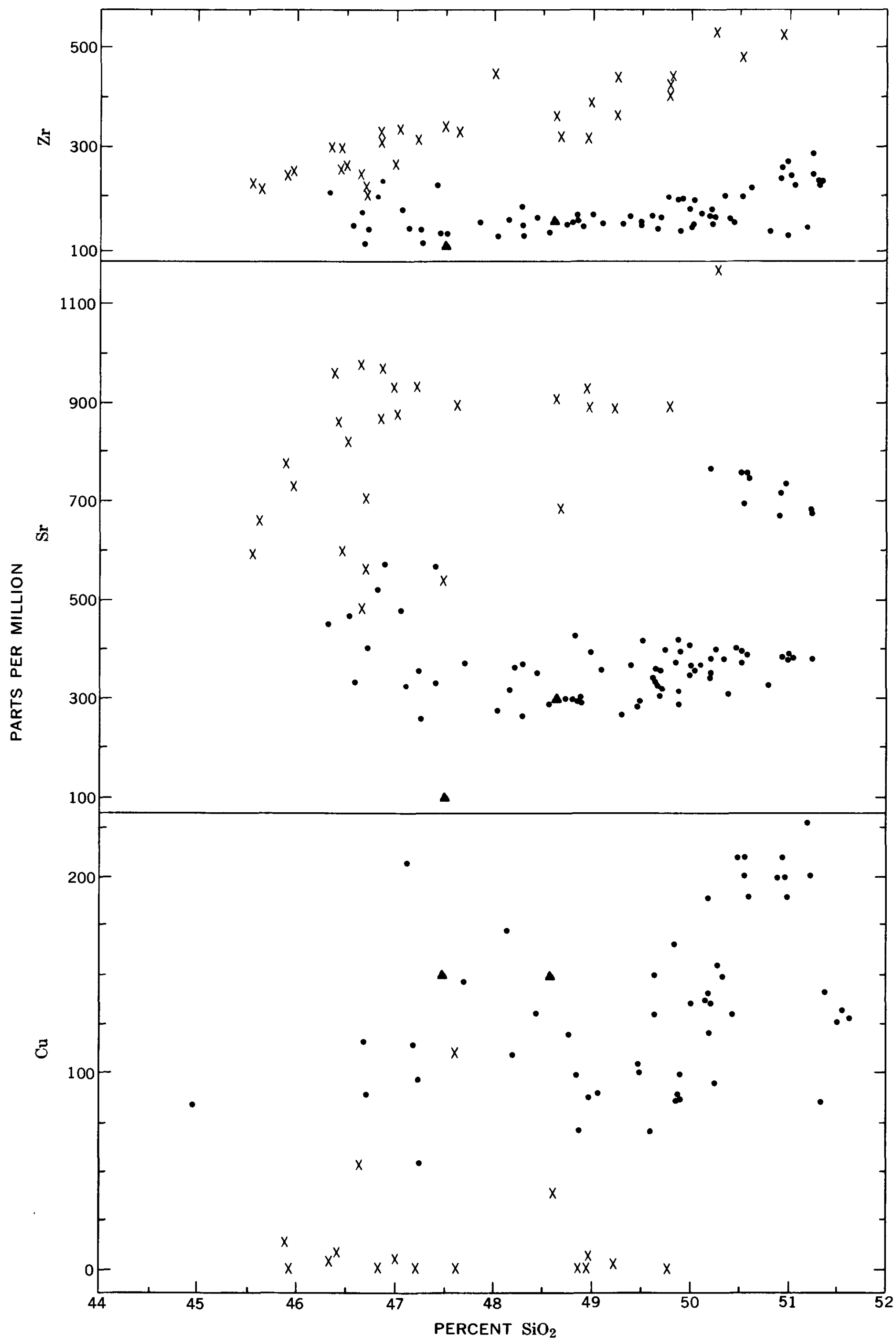
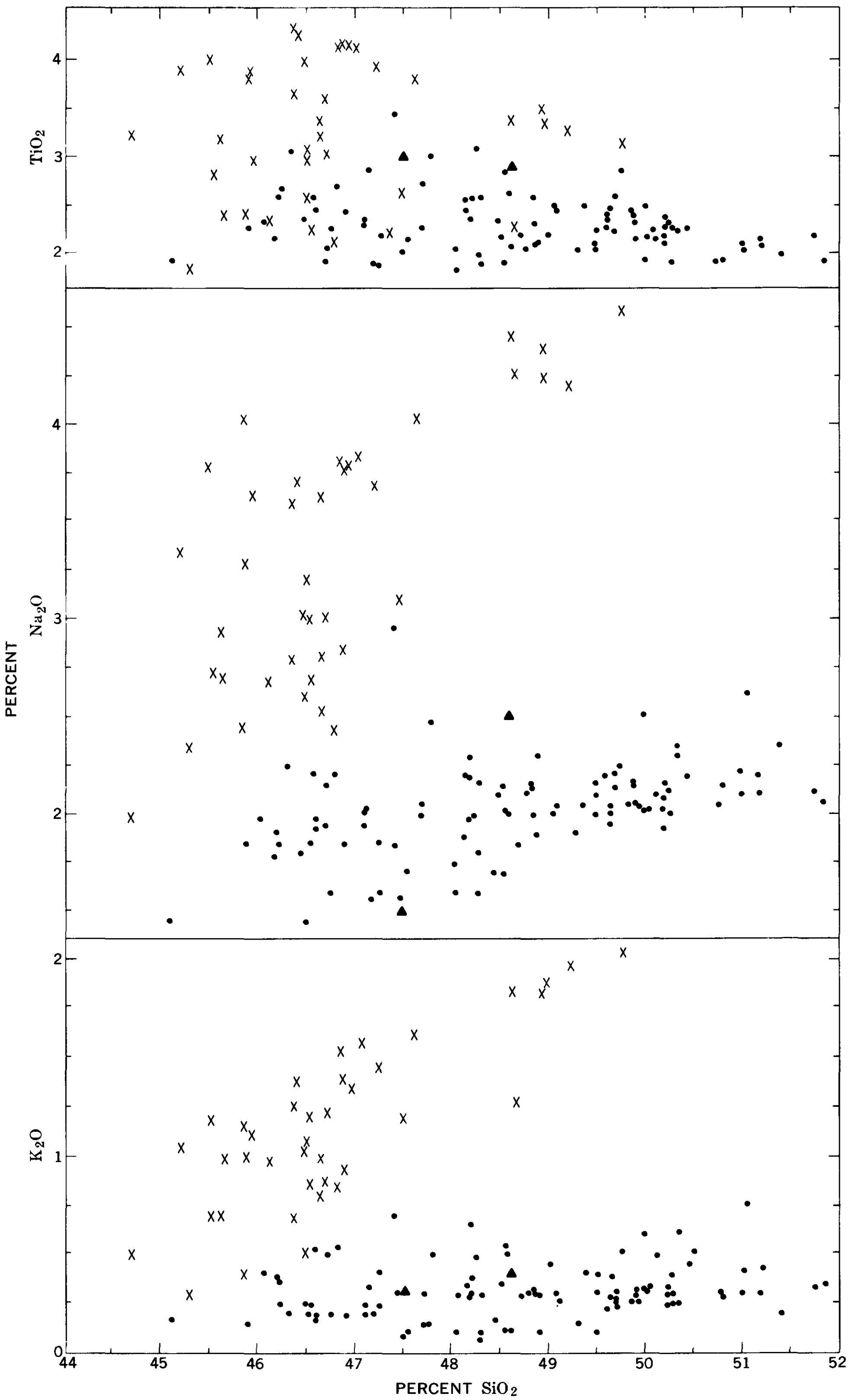


Figure 4.—The abundance of alkalies, titania, copper, strontium, and zirconium in relation to silica in Hawaiian tholeiitic and alkalic rocks and in the analyzed samples from the Midway basalts. (Data on alkalies and titania in Hawaiian rocks from Macdonald and Katsura, 1964, and Macdonald, 1968b; on strontium and zirconium from Hubbard, 1967, and Macdonald and Eaton, 1964; on copper from Herlicska, 1967, and Macdonald and Eaton, 1964, p. 87.) •; Hawaiian tholeiitic basalts; ×, Hawaiian alkalic basalts and hawaiites; ▲, Midway samples.



TiO_2
PERCENT
Na_2O
K_2O
PERCENT SiO_2
0
1
2
3
4
44
45
46
47
48
49
50
51
52

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