

31. PETROLOGY OF VOLCANIC ROCKS RECOVERED ON LEG 18

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INTRODUCTION

Volcanic rocks were recovered at five of the sites drilled on Leg 18. Preliminary shipboard petrologic studies of cored samples were augmented by onshore petrographic and petrochemical studies. At Sites 172, 173, and 178 acoustic basement was sampled. The basement consists of basalt at Sites 172 and 178 and of andesite at Site 173. At Site 177 a basalt sill was encountered in the middle of a submarine fan section. Basalt from Site 179 is similar to rocks from the adjacent Giacomini Seamount.

Major element chemical analyses of the cored rocks listed in Tables 1 to 5, were made using analytical methods described in U.S.G.S. Bulletin 1144A supplemented by atomic absorption. Trace element contents of the rocks, determined by spectrographic analysis, are also reported in Tables 1 to 5 and have an overall accuracy of ± 15 percent except near the limits of detection where only one significant figure is shown.

DESCRIPTION OF VOLCANIC ROCKS

Site 172

The volcanic rock recovered from Site 172 consists of fragments of glassy to finely crystalline basalt and palagonite up to about 5 mm in long dimension; small fragments (less than 5 mm) of phillipsite were also recovered with the basalt.

The glassy basalt fragments contain plagioclase, augite, and olivine microphenocrysts that grade serially to microlites, and sideromelane glass, palagonite, or a very fine-grained hemicrystalline matrix. The proportion of the microphenocrysts and microlites is virtually identical in all glassy fragments thin sectioned. The mode, based on 4500 points counted, is: plagioclase, 4.0%; augite, 4.4%; olivine, 0.3%; and matrix, 91.3%. The plagioclase crystals have a maximum size of about 0.5 by 0.25 mm, but most are 0.2 by 0.05 mm. Augite crystals are typically about 0.1 mm in diameter and range to 0.2 mm. Olivine crystals, mostly altered to a brown birefringent clay mineral, are about 0.05 mm in length. Plagioclase and augite, and to a lesser extent olivine, also occur as glomerophenocrysts that have a maximum diameter of 1 mm. The augite and plagioclase crystals contain minute inclusions of glass; small gas bubbles occur in this glass.

Plagioclase crystals show slight progressive zoning and have minimum N_x of 1.560 and maximum N_z of 1.575 indicating a range in composition of about An^{64} on crystal rims to An^{75} in cores of larger crystals. Augite crystals show a small range in extinction angle and are also progressively zoned. The augite has N_y about 1.695 and $2V$ about 48° , indicating a composition of approximately

$Mg_{38}Fe_{22}Ca_{40}$. Only a few olivine crystals have survived alteration and their composition was not determinable by optical methods. The sideromelane glass that makes up the bulk of these fragments is clear and light brown in color and has an index of refraction of 1.600 to 1.603. It contains a few vesicles, up to 0.15 mm in diameter, that are lined fibropalagonite. Some cracks in sideromelane are lined by fibro- or gelpalagonite, as are the rims of many sideromelane fragments. In other fragments the original sideromelane has been altered entirely to palagonite.

The microcrystalline matrix of some fragments is composed of variolitic sheaves of plagioclase, pyroxene, opaque iron-titanium oxides and hydroxides, and glass or its clay alteration products; olivine may have been present, but if it was it has been entirely altered to clay minerals. Most crystals in the matrix are less than 0.01 mm wide but sheaves of plagioclase and pyroxene are as much as 0.1 mm long. The microcrystalline matrix is too fine grained for mineral proportions to be determined.

The glassy to very finely crystalline nature of the fragments indicates rapid quenching by water. Most likely the fragments are from a tuff-breccia or pillow flow. The phillipsite fragments may have formed a cement in the breccia or between pillows.

Pieces of relatively fresh basalt from the core were hand picked for chemical analysis. As many of the pieces had small discontinuous rims of palagonite, they were ground to less than 0.3 mm and the palagonite and any enclosed crystals in palagonite were removed by flotation in bromoform. The bromoform density was adjusted to less than that of plagioclase so that the bulk composition of the fragments was not significantly altered other than by removal of palagonite and enclosed crystals. It was not feasible to remove all palagonite without grinding the sample to a finer size. Further grinding would have resulted in separation of enclosed crystals from the palagonite, thereby changing the ratio of crystals to glass, palagonite, or fine-grained matrix. The chemical analysis and norm of fragments of glassy basalt from Site 172 are shown in Table 1a. The original analysis is listed along with this analysis recalculated water-free to 100%. The norm was calculated using the original Fe_2O_3/FeO and also using a ratio of 1/9; the Fe_2O_3/FeO of the magma from which the rock was derived most likely was intermediate between these two values. By both calculations the rock is quartz normative and on the basis of normative classification, the rock is a tholeiitic basalt. Compared with average oceanic ridge tholeiitic basalts and tholeiitic olivine basalts from the Juan de Fuca and Gorda ridges, it has somewhat higher SiO_2 , total iron oxide, and K_2O and lower content of MgO and CaO . With the exception of SiO_2 and MgO , however,

TABLE 1a
Chemical Analysis and Norm of Basalt from Site 172

Chemical Analysis			
	Site 172		Average Juan de Fuca and Gorda Ridge Basalt ^b (Water Free)
	Original Analysis ^a	Water-Free Analysis	
SiO ₂	51.0	52.1	50.5
Al ₂ O ₃	13.3	13.6	15.3
Fe ₂ O ₃	3.1	13.9	11.0
FeO	10.95		
MgO	5.4	5.5	7.0
CaO	9.3	9.5	11.2
Na ₂ O	2.4	2.4	2.7
K ₂ O	0.35	0.36	0.18
H ₂ O ⁺	1.2	—	—
H ₂ O ⁻	0.21	—	—
TiO ₂	2.0	2.0	1.8
P ₂ O ₅	0.44	0.45	0.15
MnO	0.18	0.18	0.16
CO ₂	0.05		
Norm			
	Original Fe ₂ O ₃ /FeO	Fe ₂ O ₃ /FeO 1/9	
Q	6.9	4.8	
Or	2.1	2.1	
Ab	20.7	20.7	
An	25.0	25.0	
Di:	Wo 8.0	8.0	
	En 3.9	3.4	
	Fs 4.0	4.6	
	En 9.8	10.3	
Hy:			
	Fs 10.1	14.0	
Mt	4.6	2.1	
Il	3.9	3.9	
Ap	1.1	1.1	

^aAnalytical methods used are those described in USGS Bulletin 1144A supplemented by atomic absorption.

^bAverage of 17 analyses of basalt from Kay *et al.*, 1970, Table 3.

all the oxides fall within the range in percent of the individual oxides for 17 analyzed basalts from these two spreading centers. Other analyzed abyssal tholeiites from both the Atlantic and Pacific oceans also contain slightly less SiO₂ and more MgO than the Site 172 basalt. Most oceanic ridge basalts are olivine normative; those that are quartz normative generally contain less Q than does the tholeiitic basalt from Site 172. The Di/Di+Hy ratio (0.4-0.44) of the Site 172 basalt is also somewhat less than that for basalt from the Juan de Fuca and Gorda ridges. The slightly higher K₂O content at Site 172 compared with most ridge basalts is particularly significant and may indicate that it is not of ridge origin. Only 2 of 17 analyzed basalts from Juan de Fuca and Gorda ridges contain more than 0.22 K₂O (see Kay *et al.*, 1970, Table 3); basalt from Site 172 has 0.35% K₂O. In respect to many of the oxides the chemical composition of basalt from Site 172 appears to fall between values typical of tholeiitic basalts from spreading ridges and tholeiitic basalts from some seamounts and oceanic islands. The basalt may be the produce of

eruption of slightly differentiated basalt away from the ridge crest.

The trace element abundances of basalt from Site 172 (Table 1b) are generally similar to those reported by Engel *et al.* (1965) for oceanic tholeiitic basalt except that the Site 172 basalt contains greater than normal Zr and Y and less Cr and Ni. Except in these four elements the Site 172 basalt differs from average alkali basalt as reported by Engel *et al.* (1965). The content of Sr (130 ppm) and the Ba/Sr ratio (0.18) of the basalt are similar to values reported by Gast (1968, Fig. 5) and Kay *et al.* (1970 Fig. 11 and Table 4) to be typical of abyssal basalts. The Ni/Cr (0.33) is also similar to oceanic basalt according to the data of Kay *et al.* (1970, Fig. 11).

Site 173

Volcanic rock was recovered in both the extended barrel and core catcher of Cores 37 and 38 at Site 173. The samples are mostly small fragments less than 2 cm across; the largest fragment is 5 cm in largest dimension. Fragments of hard rock were incorporated in the sediment of Cores 32, 35, and 36, but their cherty lithology and rounded shapes suggest they are clasts from the sediment column or from thin lithified beds. The volcanic fragments from the bottom of the hole are glassy to aphanitic and contain small feldspar phenocrysts. The fragments are gray, purple, or green and many are extensively altered. Rims of many fragments are altered, and small veins filled with opaline material occur in others. All fragments contain numerous vesicles. Although the chips are too small to show the gross structure of the rock body, it seems likely, considering the amount of glassy and very fine-grained chips, that they are from a subaqueous breccia or pillow-breccia flow.

TABLE 1b
Trace Element Abundances (Spectrographic
Analysis, ppm) of Site 172 Basalt Compared
to Average Composition of Oceanic Tholeiitic
Basalt and Alkali Basalt

	Site 172 ¹	Average Oceanic Tholeiitic Basalt ^b	Average Alkali Basalt ^b
Ba	24	14	498
Co	40	32	25
Cr	150	297	67
Cu	69	77	36
Ga	17	17	22
La	N30	<80	90?
Nb	N15	<30	72
Ni	50	97	51
Sc	62	61	26
Sr	130	130	815
V	350	292	252
Y	100	43	54
Yb	12	5	4
Zr	320	95	333

¹Site 172 analysis results are reported to two significant figures and have an overall accuracy of $\pm 15\%$ except that they are less accurate near the limits of detection where only one digit is intended. N = Not detected at value shown.

^bEngel *et al.*, 1965, Table 2.

In thin section the volcanic rock is porphyritic-seriate with phenocrysts, microphenocrysts, and microlites of plagioclase and altered olivine that are set in very light brown glass or in a hemicrystalline matrix. Half of the thin sections also contain hypersthene phenocrysts or xenocrysts. Several sections contain quartz xenocrysts about 1 mm in length that have well-developed clinopyroxene reaction rims. Vesicles lined by phillipsite(?) and another zeolite, as well as by clay minerals, constitute 1 to 5% of the rock and are most abundant in rocks with a high glass content. Vesicles in thin section are as much as 1.3 mm across but typically are 0.5 to 1 mm across. In hand specimen, some crystal-lined vesicles several mm across were observed.

The plagioclase crystals range serially from phenocrysts 5-1/2 mm by 2-1/2 mm down to microlites less than 0.1 mm long. Phenocrysts are euhedral to subround in shape; microlites are euhedral. Larger phenocrysts have inclusions of glass or finely crystalline material in their cores that appear to reflect an early partial resorption and a few have apatite crystal inclusions. Some small clear glass(?) inclusions in the plagioclase contain minute gas bubbles. The plagioclase phenocrysts show both progressive and oscillatory zoning whereas microphenocrysts and microlites show only progressive zoning. Plagioclase separated from one sample has N_x (minimum) = 1.550 and N_z (maximum) = 1.567 indicating a range composition of about An_{40} to An_{61} ; phenocrysts are labradorite and groundmass plagioclase is andesine. Smaller plagioclase crystals also occur as gemeroporphyritic clots with olivine. A few 1/2 to 1 mm wide plagioclase "clots" consist of numerous individual crystals interlocked with a hornfelsic texture. Some of these clots contain garnet(?) inclusions and are probably xenoliths.

Pseudomorphs of former olivine phenocrysts up to 1 mm wide and microlites as small as 0.1 mm are common. They are composed of green to tan phyllosilicate minerals but many display the characteristic olivine crystal shape. Because of the alteration the modal olivine determined by point counting (3 to 6%) is only approximate. Minute opaque minerals occur on or near the crystal margins of former olivine but appear to be an alteration product rather than a reaction rim; no pyroxene reaction rims were observed.

Hypersthene phenocrysts or xenocrysts occur in half the samples studied. They commonly are irregular in shape and some crystals are deeply embayed and have irregular patches of glass developed in their cores as a result of resorption. Some hypersthene crystals have poorly developed exsolution lamellae and patches. The hypersthene has 2V of about 60° , indicating a composition of about En_{65} .

The phenocrysts, microphenocrysts, microlites, and xenocrysts are set in a matrix that ranges from glassy to hemicrystalline. The isotropic glassy matrix is clear light tan. Alteration to clay minerals (fibropalagonite) has occurred along cracks and halos of minute crystallites radiate outward from most phenocrysts and microlites. The matrix of other sections ranges from glass with abundant minute pyroxene crystallites that produce an almost opaque tachylite, to rocks with 0.05 to 0.2 mm long

pyroxene and plagioclase crystals with interstitial greenish clay and brown glass dusted by crystallites. The pyroxene in the matrix appears to be entirely augite and it contains numerous opaque mineral inclusions. Some of the green clay mineral in the interstices may fill small amygdules, most of it, however, probably developed in place during deuteric alteration.

The abundance of phenocrysts, xenocrysts, and xenoliths in the rock, the oscillatory zoning of the phenocrysts, and evidence of partial resorption indicate a complex history before the lava underwent final solidification. The clots of hornfelsic plagioclase, the quartz xenocrysts, and perhaps the hypersthene crystals may have been torn from wall rocks as the magma ascended to the surface. The abundance of glass and particularly the development of an entirely glass matrix in some samples indicates subaqueous eruption.

Modal analyses of four samples of varying degree of crystallinity are given in Table 2a. Chemical and trace element analyses of the most crystalline rock are shown in Tables 2b and 2c where they are compared to analyses of various rock types.

Both the original analysis (Core 38) and this analysis recalculated water-free to 100% are given in Table 2b. The original analysis gives 6.3% H_2O ; this and, the high oxidation state of iron, indicates the high degree of alteration of the rock. The norm was calculated with the original Fe_2O_3/FeO and a ratio of 1/9; the original oxidation state of the iron probably was between these two extremes. The rock is quartz-normative and its normative plagioclase is An_{49} , essentially at the commonly accepted An_{50} division between basalt and andesite.

The average composition of andesite according to Nockolds (1954) is also listed in Table 2b. The volcanic rock from Site 173 is very similar in chemical composition to the average andesite. The composition of the volcanic rock from Site 173 is similar to some Tertiary and Quaternary basaltic andesites from the Cascade Range, two of which are listed in Table 2b for comparison. The Site 173 andesite differs in composition from typical abyssal basalts and from most rocks of similar SiO_2 content from seamounts and oceanic islands which commonly are not quartz normative.

TABLE 2a
Modal Analyses of Andesite from Site 173

Sample	Modal Analyses			
	38B	37A	37B	38A
Vesicles and amygdules	5	4	3	1
Plagioclase	9	11½	16	27
Augite	—	trace	—	11
Hypersthene	½	½	—	—
Olivine	6	6	3	4
Glass, microcrystalline matrix and alteration products of indeterminate minerals	79½	78	78	57

TABLE 2b
Chemical Analysis and Norm of Volcanic Rock from Site 173 (Core 38)

Chemical Analysis					
	Site 173			Miocene Basaltic Andesite, Sardine Formation, Cascade Range, Oregon, Water Free ^c	Basaltic Andesite Crater Lake, Ore., Water Free ^d
	Original Analysis ^a	Water-Free Analysis	Average Andesite Water Free ^b		
SiO ₂	51.3	55.1	54.4	55.1	56.7
Al ₂ O ₃	16.6	17.8	17.8	17.0	18.3
Fe ₂ O ₃	5.0	8.3	9.0	10.4	6.8
FeO	2.7				
MgO	5.0	5.4	4.4	3.5	5.2
CaO	6.6	7.1	7.9	6.8	7.5
Na ₂ O	3.3	3.5	3.7	4.1	3.7
K ₂ O	1.1	1.2	1.1	1.0	1.2
H ₂ O ⁺	2.1	—	—	—	—
H ₂ O ⁻	4.2	—	—	—	—
TiO ₂	1.2	1.3	1.3	1.6	0.85
P ₂ O ₅	0.26	0.28	0.28	0.18	0.11
MnO	0.06	0.06	0.15	0.22	0.08
CO	0.05	0.05	—	0.18	—
Norm					
	Original Fe ₂ O ₃ /FeO	Fe ₂ O ₃ /FeO = 1/9			
Q	8.4	3.5			
Or	7.0	7.0			
Ab	30.0	30.0			
An	29.2	29.2			
	Wo	1.7			
Di:	En	1.5		0.91	
	Fs	0		0.74	
	En	11.9		12.5	
Hy:					
	Fs	0		10.1	
Mt	5.8	1.2			
Il	2.4	2.4			
Ap	0.66	0.66			

^aAnalytical methods used are those described in USGS Bulletin 1144A supplemented by atomic absorption.

^bFrom Nockolds, 1954.

^cFrom Peck *et al.*, 1964, Table 7, Col. 8.

^dFrom Williams, 1942, Anal. 10.

Comparison of trace element abundances of the analyzed andesite from Site 173 with average abundances of oceanic tholeiitic basalt, alkali basalt, andesite, and low silica andesite. Table 20 shows that relative to oceanic basalt the andesite from Site 173 contains significantly greater quantities of the large cations, Ba, Sr, and Zr, and lesser quantities of the "ferromagnesian" elements Co, Cr, Cu, Ni, Sc, and V, and similar or lesser quantities of the rare earths, Y and Yb. The Ba/Sr ratio (1.3) of the Site 173 andesite is much greater than that of oceanic basalt reported by Gast (1968, Fig. 5) which ranges approximately from 0.01 to 0.24. Also the Ni/Cr ratio (0.05) is much less than Gast (1968, Fig. 6) reports to be typical of oceanic tholeiites (0.25 to about 0.7). The Site 173 andesite also differs markedly in content of some of the trace elements, particularly Cr, Nb, Ni, and Sr, from average

alkali basalt as listed by Engel *et al.* (1965). Although in respect to content of many of the trace elements, the Site 173 andesite is similar to average andesite and low silica andesite of Taylor (1969); it contains significantly greater Ba, Cr, and Y, and less Cu and Zr.

Site 177

Hard rock was penetrated in a drilled interval at 381.5 meters. Drilling was stopped to take Core 24, which recovered 190 cm of hard, dark greenish gray to black basalt. Core 25 penetrated 160 cm of basalt and then broke through into sediment again. The drilling penetration record indicates that the total thickness of basalt in the section is about 5 meters. The seismic record suggests it is contained in a fault zone.

TABLE 2c
Trace Element Abundances (Spectrographic Analysis, ppm)
in Site 173 Andesite Compared to Average Composition
of Other Rocks

	Site 173 ^a	Average Oceanic Tholeiitic Basalt ^b	Average Alkali Basalt ^b	Average Andesite ^c	Average Low-Si Andesite ^c
Ba	560	14	498	270	200
Co	23	32	25	24	28
Cr	190	297	67	56	85
Cu	20	77	36	54	60
Ga	15	17	22	16	13
La	N30	<80	90?	12	10
Nb	N15	<30	72	4	4
Ni	15	97	51	18	28
Sc	32	61	26	30	11
Sr	420	130	815	385	430
V	160	292	252	175	200
Y	36	43	54	21	22
Yb	4	5	4	2	2
Zr	200	95	333	110	92

^aSite 173 analysis results are reported to two significant figures and have an overall accuracy of +15% except that they are less accurate near the limits of detection where only one digit is intended. N = Not detected at value shown.

^bEngel et al., 1965, Table 2.

^cTaylor, 1969, Tables 1-6.

The apparent massive nature of the basalt body suggests it is probably a dike or sill; however, an extrusive origin cannot be discounted. The underlying sediment and the hard carbonate-cemented sediment below the contact here slickensided fractures that might be associated with intrusion, but the fracturing and vein-filling in the basalt itself and slickensides found in sediments above the body indicate post-solidification fracturing. The overall tectonic setting of the drill site suggests that the basalt body may be in fault contact with the adjacent sediments.

The basalt core consists of approximately 35 hard, rounded blocks 5 to 15 cm in length. The cored rock is various shades of gray and green and has several fractures and vein-filled fractures at various angles to the length of the core. The cracks are filled with soft greenish chlorite and aragonite and have slick green surfaces.

The lower contact of the basalt and mudstone is shown in one sample. The mudstone is slightly baked at the contact to produce greater than normal induration but shows no apparent increase in grain size nor development of incipient porphyroblasts. Considering the thickness of the basalt body (about 5 m), no marked contact metamorphic effects would be expected. Calcite fills fractures in the indurated mudstone at and near the contact and also occurs in the basalt with aragonite along small fractures in the interior of the body.

Within 2 to 3 cm of the contact the basalt contains scattered clay-filled amygdules, typically 0.5 mm across. The basalt is microporphyrritic-seriate and contains a few plagioclase phenocrysts 1 to 2 mm long as well as plagioclase microphenocrysts that range from a maximum of 0.2 by 1 mm serially down to microlites that are 0.02 by

0.2 mm. The microlites commonly have forked terminations and curved shape. Olivine microphenocrysts that are entirely altered to clay minerals occur with the plagioclase and are typically 0.2 mm wide. The plagioclase and olivine microphenocrysts tend to occur in irregular clots. Both minerals contain small (0.01 to 0.05 mm) reddish brown spinel octahedra. The microphenocrysts and microlites are set in a very fine-grained hemicrystalline matrix composed of pyroxene, plagioclase, opaque minerals, and clay minerals. Most of the clays probably have replaced former glass. The pyroxene in the matrix commonly occurs as groups of parallel-oriented, irregularly shaped elongate crystals. The grain size of the matrix increases towards the center of the body.

In the interior of the body, the texture becomes subophitic and the plagioclase has a variable grain size that is typically 0.1 to 0.5 mm; several 2 mm plagioclase phenocrysts were observed. Samples from near the center of the body contain about 45% plagioclase, 30 to 35% augite, and 1/4% spinel in addition to very fine-grained pyroxene, opaque minerals, and clay minerals that occur sporadically in the interstices between larger mineral grains. Some clay appears to be pseudomorphic after olivine, but determination of the proportion of original olivine is subjective because similar clays occur also in the matrix as an alteration product of glass. Pyroxene is fresh, plagioclase is dusted in places with alteration products.

Plagioclase shows progressive zoning and cores of larger crystals range in composition from about An₆₅ to An₆₈; smaller crystals and outermost rims of larger crystals are more sodic. Pyroxene crystals appear to be generally uniform in composition except adjacent to the fine-grained matrix or where they are zoned to a darker brown color, probably indicating an increase in Fe and (or) Ti content. Most of the pyroxene has $N_y = 1.687-1.691$ and $2V = 51^\circ$, indicating a composition of about Ca₄₂Mg₄₃Fe₁₅. The opaque minerals in the finely crystalline residue were not studied in polished section but appear in thin section to be mainly magnetite_{ss} with lesser ilmenite_{ss}. Rare, minute red hematite plates were also noted. A few clay and calcite-filled amygdules about 0.3 mm across occur in the basalt. Modal analysis of four samples from the basalt body based on 1000 or more points per sample are shown in Table 3a.

A chemical analysis and morm of the basalt from Hole 177A (sample 24-140 cm) are shown in Table 3b. The

TABLE 3a
Modal Analyses of Basalt from Site 177

Sample	25-116	24-10	24-114	24-140
Plagioclase	19½	40	46½	43
Olivine ^a	7½	10	8½	8
Spinel	¼	¼	¼	¼
Pyroxene		35	29½	34
Matrix ^b	72	14½	15½	14½
Amygdules	¼	¼	—	¼

^aEntirely replaced by clay minerals, proportion shown is approximate.

^bVery fine-grained opaque minerals, pyroxene, and clay minerals (after glass?).

TABLE 3b
Chemical Analysis and Norm of Basalt from Site 177

Chemical Analysis			
	Site 177		Average Juan de Fuca and Gorda Ridge Basalt ^b (Water Free)
	Original Analysis ^a	Water-Free Analysis	
SiO ₂	48.7	50.6	50.5
Al ₂ O ₃	16.8	17.5	15.3
Fe ₂ O ₃	3.0	3.1	11.0
FeO	4.8	5.0	
MgO	7.4	7.7	7.0
CaO	11.8	12.3	11.2
Na ₂ O	2.3	2.4	2.7
K ₂ O	0.03	0.03	0.18
H ₂ O ⁺	1.3	—	—
H ₂ O ⁻	2.2	—	—
TiO ₂	1.1	1.1	1.8
P ₂ O ₅	0.14	0.14	0.15
MnO	0.11	0.11	0.16
CO ₂	0.05	0.12	—

Norm		
	Original Fe ₂ O ₃ /FeO	Fe ₂ O ₃ /FeO 1/9
Q	2.0	—
Or	0.18	0.18
Ab	20.2	20.2
An	36.8	36.8
Di:		
Wo	9.7	9.7
En	7.0	5.8
Fs	1.8	3.3
En	12.2	11.5
Hy:		
Fs	3.1	6.6
Fo		1.3
Fa		0.81
Mt	4.5	1.2
Il	2.2	2.2
Ap	0.32	0.32

^aAnalytical methods used are those described in USGS Bulletin 1144A supplemented by atomic absorption.

^bAverage of 17 analyses of basalt from Kay et al., 1970, Table 3.

analysis is shown both as the original and recalculated water-free to 100% and the norm is shown calculated on the original analysis as well as with Fe₂O₃/FeO of 1/9. Depending on the original oxidation state of the iron which probably lay between the observed Fe₂O₃/FeO of 3/4.8 and an arbitrarily assigned value of 1/9, the rock is normatively a tholeiitic basalt or tholeiitic olivine basalt. The alteration of the 8 to 10% former olivine in the rock probably accounts largely for the relatively high ferric iron content, and the former unaltered rock was most likely an olivine normative tholeiitic olivine basalt. Its composition is very similar to that of ridge basalts dredged from the nearby Juan de Fuca Ridge and the Gorda Ridge, whose average composition of which is also shown in the table. The content of Al₂O₃ and total iron in the Site 177 basalt differs somewhat from the average ridge basalt, but a few of

the seventeen analyses used to compile the average have similar Al₂O₃ and total iron contents. Particularly significant is the low K₂O content of the Site 177 basalt (0.03), as low K₂O is of oceanic ridge basalts.

Trace element abundances of the tholeiitic basalt from Site 177 are compared in Table 3c with average oceanic tholeiitic basalt and alkalic basalt, and also with average tholeiitic basalt of Kilauea, Hawaii. With respect to most trace elements, the Site 177 basalt is most similar to average oceanic tholeiitic basalt, although it does contain somewhat greater Co, Cr, Ni, and Sr than average oceanic tholeiite of Engel et al. (1965, Table 2). Other workers (e.g. Gast, 1968), however, report contents of these four elements in oceanic tholeiitic basalt similar to those of the basalt of Site 177. The Ba/Sr ratio (0.075), Ni/Cr ratio (0.4), and the content of Ba, Sr, Ni, and Cr are typical of oceanic tholeiitic basalt according to the data of Gast (1968, Fig. 5). Trace element abundances of tholeiitic basalt from the nearby Juan de Fuca Ridge are also similar to Site 177 basalt according to the data of Kay et al. (1970). Site 177 basalt differs in content of many trace elements from average alkalic basalt and average Kilauea tholeiitic basalt. Particularly notable are the much lower contents in the Site 177 basalt of Ba, La, Nb, Sr, and Zr.

Site 178

Hole 178 penetrated 17 meters of basalt at the bottom and recovered 40 cm of hard-rock core. The depth to the basalt corresponds closely to depth to acoustic basement in the reflection records.

TABLE 3c
Trace Element Abundances (Spectrographic Analysis, ppm) in Site 177 Tholeiitic Basalt Compared to Average Composition of Oceanic Tholeiitic Basalt and Alkali Basalt

	Site 177 ^a Tholeiitic Basalt	Average Oceanic Tholeiitic Basalt ^b	Average Alkalic Basalt ^b	Average Kilauea, Hawaii Tholeiitic Basalt ^c
Ba	15	14	498	184
Co	54	32	25	46
Cr	380	297	67	252
Cu	91	77	36	207
Ga	15	17	22	18
La	N30	<80	90?	NR
Nb	N15	<30	72	NR
Ni	150	97	51	164
Sc	55	61	26	34
Sr	200	130	815	652
V	300	292	252	339
Y	42	43	54	50
Yb	4	5	4	NR
Zr	74	95	333	202

^aSite 177 analysis results are reported to two significant figures and have an overall accuracy of +15% (except that they are less accurate near the limits of detection where one digit is intended. N = Not detected at values shown.

^bEngel et al., 1965, Table 2.

^cPrinz, 1967, Table 4.

In hand specimen, the basalt core is massive and dark gray. Several chilled glassy basalt selvages in the cores may be margins of pillows. Veinlets about 2 mm wide are common in the basalt. They are filled by calcite and aragonite. In thin section the rock ranges from glass with scattered microphenocrysts of olivine to coarse-grained holocrystalline basalt. Between the two extremes are rocks that show progressive crystallinity and that are particularly notable because of the feathery texture of the quenched olivine.

The finest grained basalt samples are microporphyritic and glassy. They consist of 4 to 10% olivine microphenocrysts that are irregularly dispersed in a glassy matrix. The glass appears black (tachylite) in thin section, but, in conoscopic light on thin edges of sections, the tachylite can be seen to consist of exceptionally fine-grained variolitic crystalline phases, probably largely pyroxene, olivine, plagioclase, and opaque minerals, in addition to glass. The olivine microphenocrysts are typically 0.1 to 1.5 mm in longest dimension. Although many are euhedral, others are marked by irregular reentrants filled by tachylite or contain round inclusions of tachylite in their cores. The olivine microphenocrysts contain small dark yellowish brown spinel euhedra. The olivine has $N_x = 1.668$, $N_y = 1.6885$, and $N_z = 1.708$ indicating a composition of about Fo_{81} . X-ray diffraction patterns also indicate a composition of Fo_{80-81} according to the method of Hotz and Jackson (1963), but Fo_{85} according to that of Yoder and Sahama (1957).

With a slight increase in grain size the matrix becomes variolitic and contains pyroxene, olivine, plagioclase, and opaque minerals along with microphenocrysts of olivine similar to those in the glassy rocks. Most groundmass crystals in the finer grained samples are less than 0.4 mm long and tend to be markedly elongate. Olivine in the groundmass occurs as very elongate crystals typically 0.02 X 1 mm, that occur scattered through the matrix. Some of these elongate olivines occur as spearlike projections from equant olivine microphenocrysts; many are developed on microphenocryst terminations parallel to the C direction. Many of the small elongate olivine crystals occur as discontinuous chains of grains; others have very irregular borders. Similar olivine crystals in tholeiitic olivine basalt from the mid-Atlantic Ridge are described by Aumento (1968). The elongate olivine in the basalt is most likely a product of relatively rapid quenching. Similar olivine habit has been reported in laboratory-quenched melts of approximately basaltic composition. The olivine microphenocrysts and elongate olivine are extensively altered to clay minerals, serpentine(?), and hydrous iron oxides, or to calcite. Plagioclase in the variolitic matrix also is partly altered.

A continuous change is shown from microporphyritic basalt with a very fine-grained variolitic matrix to rocks with much coarser grain size. The basalt is composed of plagioclase, pyroxene, olivine, opaque minerals, and trace amounts of brown spinel, in addition to abundant clay minerals that replace plagioclase and olivine. Much clay occurs in the interstices and seems to replace former glass. The plagioclase crystals show a large range in grain size; some are as much as 2 mm long; others are only 0.1 mm. The larger crystals are progressively zoned from An_{60} to

An_{69} in crystal cores to about An_{55} on the rims. Smaller crystals are probably similar in composition to rims of larger crystals. The smaller crystals are in places intergrown with pyroxene in subophitic fashion. The pyroxene commonly occurs as sets of parallel-oriented crystals 0.5 mm in long dimension or smaller. The pyroxene separated from one sample has N_y about 1.72 and $2V$ about 53° . The color of the pyroxene ranges from light pinkish brown to brownish lavender and pleochroism and dispersion are noticeable. The color, pleochroism, and dispersion indicate a relatively high Ti content in the augite. Olivine crystals comprise about 10% of the coarser rocks and are mostly altered, but a few of the coarsest grained sections had no olivine. Opaque minerals, which based on shape in transmitted light appear to be both ilmenite_{ss} and magnetite_{ss}, comprise up to 5% of the basalt. Modal analyses of typical samples of the basalt based on 1000 or more points per section are shown in Table 4a. Alteration products of minerals were counted with the mineral they replace where determinable.

A chemical analysis and norm of basalt from Site 178 (Core 59 bottom) are shown in Table 4b. The analysis is shown both as the original and recalculated water- and calcium carbonate-free. Removal of calcium carbonate reduces the CaO content by only 0.3% which results in a decrease in normative Wo of 0.6%; both norms shown are calcium carbonate-free. The norm is shown calculated with the analyzed Fe_2O_3/FeO ratio of 7.3/5.9 and with a ratio of 1/9. The high ferric iron and water content reflect alteration that is shown by thin sections of the rock. Using the 7.3/5.9 iron ratio the rock is quartz normative; however, prior to alteration this ratio was almost certainly much lower, and the rock probably originally had a normative composition more nearly like the strongly olivine normative composition calculated using Fe_2O_3/FeO of 1/9. The high olivine content in the rock (as much as 14%) also indicates that the original rock was olivine normative. According to normative classification the Site 178 volcanic rock is a tholeiitic olivine basalt. Compared with an average of oceanic ridge basalts from the Juan de Fuca and Gorda ridges, it contains more total iron, MgO, and K_2O , and less CaO and SiO_2 . Several of the basalts from these ridges, however, have similar contents of all but K_2O . The Site 178 basalt differs from these ridge basalts in a manner similar to that of the somewhat more siliceous tholeiitic basalt from

TABLE 4a
Modal Composition of Basalt from Site 178

Sample	58A	59D	59B	59C
Olivine	2	4	14	12
Pyroxene	—	—	27	27
Plagioclase	—	—	41	44
Brown spinel	Trace	Trace	Trace	Trace
Opaque minerals	—	—	4	5
Indeterminate minerals and (or) fine-grained or glassy matrix	98	96	14	13

TABLE 4b
Chemical Analysis and Norm of Basalt from Site 178 (Core 59,

Chemical Analysis						
	Original Analysis ^a	Site 178 Water and CaCO ₃ -free Analysis	Average Juan de Fuca and Gorda Ridge Basalt ^b (Water Free)	Alkali Basalt Giacomini Seamount ^c (Water Free)	Alkali Basalt Kodiak Seamount ^d (Water Free)	
SiO ₂	45.8	48.1	50.5	48.6	47.1	
Al ₂ O ₃	14.9	15.6	15.3	16.7	17.7	
Fe ₂ O ₃	7.3	7.7	11.0	13.7	13.6	
FeO	5.5	5.8	7.0	1.7	2.6	
MgO	8.0	8.4	11.2	8.3	8.1	
CaO	2.7	2.8	2.7	4.9	4.3	
Na ₂ O	0.37	0.39	0.18	1.8	1.8	
K ₂ O	2.3	—	—	—	—	
H ₂ O ⁺	1.8	—	—	—	—	
H ₂ O ⁻	1.6	1.7	1.8	2.5	3.4	
TiO ₂	0.44	0.46	0.15	1.9	1.2	
P ₂ O ₅	0.08	0.08	0.16	0.14	0.17	
MnO	0.26	—	—	—	—	
CO ₂						

Norm				
		Original Fe ₂ O ₃ /FeO	Fe ₂ O ₃ /FeO 1/9	
	Q	1.5	—	
	Or	2.3	2.3	
	Ab	24.0	24.0	
	An	28.8	28.8	
	Di:			
	Wo	5.6	5.6	
	En	4.6	2.9	
	Fs	0.36	2.6	
	En	16.3	5.7	
	Hy:			
	Fs	1.3	5.0	
	Fo	—	8.6	
	Fa	—	8.4	
	Mt	11.1	2.0	
	Il	3.2	3.2	
	Ap	1.1	1.1	

^aAnalytical methods used are those described in USGS Bulletin 1144A supplemented by atomic absorption.

^bAverage of 17 analyses of basalt from Kay et al, 1970, Table 3.

^cFrom Forbes et al, 1969, Table 1, col. 1.

^dFrom Forbes and Hoskin, 1969, Table 1, col. 7.

Site 172. Both of these basalts may have been produced by continued eruption of slightly differentiated basalt away from a ridge crest. Alteration of the Site 178 basalt, however, may have produced some of the observed chemical anomalies (see Hart, 1970). The Site 178 tholeiitic olivine basalt differs in composition from alkalic basalt (hawaiiite) and trachyte from the nearby Kodiak and Giacomini seamounts, analyses of which are also shown in Table 4b. Many seamounts and oceanic islands, however, have a veneer of alkalic rocks over tholeiitic basalt that may be similar in composition to Site 178 basalt.

Trace element abundances (ppm) of the basalt from Site 178 are listed in Table 4c, along with those of Engel et al. (1965) for average oceanic tholeiitic basalt and alkali basalt. Site 178 basalt contains more Ba, Co, Ni, and Sr than the average oceanic tholeiitic basalt. Compared with average alkalic basalt, it contains more Cr, Cu, Ni, and Sr, and less Ba, La, Nb, and Zr. With respect to most of the listed trace

elements, it is intermediate in composition between the tholeiitic and alkalic basalt. The high Ni, Cr, and Co content may result from the relatively abundant olivine microphenocrysts and their enclosed spinel euhedra which commonly contain relatively abundant amounts of these trace elements. Although the Ba/Sr ratio (0.16) is similar to ratios of oceanic tholeiitic basalt (but much less than alkalic basalt) reported by Gast (1968), both Ba and Sr are present in much greater quantities than typical of oceanic tholeiitic basalt.

Site 179

Hole 179 bottomed in volcanic basement or a basalt conglomerate at 109 meters. Core 12 contains one large and three small pieces of weathered brown volcanic rock in the core catcher along with some brown clay. Core 13 recovered only a few angular pebbles or fragments of volcanic rock amongst many other pebbles, and Core 11

TABLE 4c
Trace Element (Spectrographic Analysis, ppm) of
Basalt from Site 178 and the Average Trace
Element Content of Oceanic Tholeiitic
Basalt and Alkalic Basalt

	Site 178 Basalt ^a	Average Oceanic Tholeiitic Basalt ^b	Average Alkalic Basalt ^b
Ba	64	14	498
Co	75	32	25
Cr	350	297	67
Cu	63	77	36
Ga	18	17	22
La	N30	<80	90?
Nb	N15	<30	72
Ni	290	97	51
Sc	40	61	26
Sr	390	130	815
V	250	292	252
Y	44	43	54
Yb	3	5	4
Zr	140	95	333

^aSite 178 analysis results are reported to two significant figures and have an overall accuracy of +15% except that they are less accurate near the limits of detection where only one digit is intended.

^bEngel et al., 1965, Table 2.

contained a bed of water-sorted basaltic sand and fine gravel bedded between zeolite-bearing red clay. As much as 0.5 meters of red clay may occur between the basaltic sand and gravel and the bottom of the hole.

The fragments of volcanic rock in Cores 12 and 13 are similar in composition. The rock is strongly weathered and in places has concentric-ringed weathered zones. The rock is very fine grained, equigranular, and hemicrystalline. It contains about 1 to 3% vesicles, 1 to 2 mm in diameter, that are lined by a zeolite(?). The fine grain size and alteration make petrographic description difficult. Plagioclase is the principal crystalline phase and comprises as much as 60% of the more crystalline rocks studied. In the finest grained rocks, however, discrete plagioclase crystals comprise only 10 to 20%, although a considerable amount may be present in the very fine grained or glassy matrix. The plagioclase occurs as flow-aligned microlites that are typically 0.1 to 0.3 mm long and 0.01 to 0.03 mm wide; a few crystals are as large as 0.2 by 0.5 mm. The plagioclase has a maximum N_z of 1.559 and minimum N_x of less than 1.552, indicating a composition of about An_{46} and less.

Plagioclase crystals show progressive zoning; the larger crystals also show oscillatory zoning. Two thin sections contain small quantities (less than 3%) of a mafic mineral that is probably olivine but might be hypersthene. This mafic mineral occurs as 0.05 to 0.3 mm long crystals, mostly altered to clay minerals that are irregularly distributed in the rock.

The matrix between plagioclase laths is composed of altered glass and extremely fine-grained crystalline phases. In thin sections of the coarsest grained rocks, altered glass is minor and the crystalline phases are sufficiently coarse to identify augite, plagioclase, alkali(?) feldspar, apatite, a zeolite(?), and goethite or hematite along with alteration products. The augite occurs as sets of parallel or radiating

feathery crystals. Individual augite crystals are much less than 0.01 mm wide and typically about 0.1 mm long. In many places they occur enclosed in plagioclase and alkali(?), feldspar. An opaque mineral, tentatively identified as magnetite, occurs as 0.05 to 0.01 mm wide equant crystals that make up 2 to 3% of the rock. Apatite occurs as minute elongate crystals enclosed in all other minerals and an apatite microphenocryst was noted in one thin section.

A chemical analysis and norm of the volcanic rock from Site 179 (Core 13) are shown in Table 5a. Both the original analysis and an analysis recalculated water-free to 100% are shown. The norm was calculated using both the reported Fe_2O_3/FeO ratio of 6.1/2.9 and an arbitrary ratio of 1/9. The high ferric iron content undoubtedly reflects alteration of the rock. Depending on the Fe_2O_3/FeO ratio, the rock is quartz normative or slightly olivine normative. The rock has a high silica and alkali content. Its chemical characteristics are similar to rocks dredged from the nearby Giacomini Seamount (Forbes et al., 1969) and from Kodiak Seamount (Forbes and Hoskins, 1969). In all of its major oxides the Site 179 volcanic rock is intermediate in composition between an alkalic andesine basalt (hawaiite) from Giacomini and trachyte from Kodiak. According to chemical parameters it is most similar to mugearite; Nockold's (1954) average mugearite is listed in the table for comparison. Most mugearites, however, contain more normative olivine and many contain normative nepheline. Although the silica content of the Site 179 mugearite is higher than Nockold's average mugearite, those from the Hawaiian Islands commonly contain this much or more silica (see MacDonald and Katsura, 1962, Fig. 2). The Site 179 mugearite differs from rocks of this same silica content on continental margins by a higher alkali content; some trachyandesites, however, are grossly similar in composition. The close proximity of Giacomini Seamount and the similarity in composition of Site 179 mugearite to rocks from the seamount (and Kodiak) suggests that it may be derived from Giacomini.

Trace element abundances in the volcanic rock from Site 179 (Core 13) are shown in Table 5b. The trace element content differs greatly from the values reported by Engel et al. (1965) for average oceanic tholeiitic and alkalic basalts and from those of Taylor's (1969) average andesite. Particularly different are the low contents of Co, Cr, Cu, Ni, and V and high abundances of Y, Yb, and Zr. In Ba, Co, Cr, Cu, Ni, and V, the rock is more similar to dacite or rhyolite as reported by Taylor (1969), but it differs markedly from them in La, Nb, Y, Yb, and Ar. The particularly high content of Zr and Nb in the volcanic rock from Site 173 suggests that it may be a product of strong fractional crystallization, inasmuch as Zr and Nb do not easily enter into lattice sites of minerals of basaltic rocks. Removal of olivine and pyroxene during fractional crystallization of basaltic magma might also have produced the low content of Co, Cr, and Ni which readily enter sites in these two minerals.

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TABLE 5a
Chemical Analysis and Norm of Volcanic Rock from Site 179 (Sample 13C)

Chemical Analysis					
	Site 179		Alkalic Andesine Basalt Giacomini Seamount (Water Free) ^b	Trachyte Kodiak Seamount (Water Free) ^c	Average Mugearite (Water Free) ^d
	Original Analysis ^a	Water-free Analysis			
SiO ₂	54.3	57.2	48.6	59.8	54.7
Al ₂ O ₃	16.5	17.4	16.7	18.8	16.7
Fe ₂ O ₃	6.1	6.4			
FeO	2.9	3.1	13.7	6.7	9.8
MgO	0.98	1.0	1.7	0.65	2.5
CaO	4.8	5.0	8.3	2.8	5.1
Na ₂ O	5.2	5.5	4.9	6.9	5.7
K ₂ O	2.5	2.6	1.8	3.3	2.8
H ₂ O ⁺	0.90	—	—	—	—
H ₂ O ⁻	2.3	—	—	—	—
TiO ₂	1.1	1.2	2.5	0.53	2.0
P ₂ O ₅	0.51	0.54	1.9	0.21	0.79
MnO	0.09	0.09	0.14	0.21	0.17
CO ₂	0.05	—	—	—	—

Norm			
		Original Fe ₂ O ₃ /FeO	Fe ₂ O ₃ /FeO 1/9
	Q	5.8	—
	Or	15.6	15.6
	Ab	46.3	46.3
	An	14.1	15.1
	Wo	2.7	2.7
Di:	En	2.4	0.48
	Fs	—	2.5
	En	0.22	2.0
Hy:	Fs	—	10.1
	Fo	—	0.09
Ol:	Fa	—	0.48
Mt		6.8	1.4
Il		2.2	2.2
Ap		1.3	1.3

^aAnalytical methods used are those described in USGS Bulletin 1144A supplemented by atomic absorption.

^bAverage of 17 analyses of basalt from Kay et al, 1970, Table 1.

^cFrom Forbes et al., 1969, Table 1, Col. 1.

^dFrom Nockolds, 1954, Table, Col. 8.

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TABLE 5b
Trace Element Abundances (Spectrographic Analysis; ppm) of
Volcanic Rock from Site 179 (Core 13) and the
Average Composition of Oceanic Tholeiitic
Basalt and Alkalic Basalt of
Engel *et al.*, (1965)

	Site 179 ^a	Average Oceanic Tholeiitic Basalt ^b	Average Alkalic Basalt ^b	Average Andesite ^c
Ba	420	14	498	270
Co	6	32	25	24
Cr	N2	297	67	56
Cu	10	77	36	54
Ga	33	17	22	16
La	110	<80	90	12
Nb	88	<30	72	4
Ni	N2	97	51	18
Sc	36	61	26	30
Sr	680	130	815	385
V	N4	292	252	175
Y	96	43	54	21
Yb	10	5	4	2
Zr	950	95	333	110

^aSite 179 analysis results are reported to two significant figures and have an overall accuracy of +15% except that they are less accurate near the limits of detection where only one digit is intended. N = Not detected at value shown.

^bEngel *et al.*, 1965, Table 2.

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