35. PETROLOGY OF BASALTIC AND GABBROIC ROCKS DREDGED FROM THE DANGER ISLAND TROUGHS, MANIHIKI PLATEAU

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ABSTRACT

Dredging in the Danger Island Troughs, which divide the High and Western parts of the Manihiki Plateau, recovered several fresh pebbles of olivine tholeiite and tholeiite, a single pebble of highly altered gabbroic cumulate, and several dozen pebbles of altered variolitic basalt. Whole-rock chemical analyses and trace element analyses indicate that two of the basalt samples are abyssal tholeiites having very high concentrations of MgO, Ni, and Cr. The samples are characterized by the presence of abundant microphenocrysts of chromite and both phenocryst and quench olivine. The basalt samples show concentrations of SiO2, Al2O3, CaO, Na2O, TiO2, Cu, Zn, V, Pb, Rb, and Ba increasing as MgO decreases and concentrations of Cr, Ni, Co, Nb (?), and Sc (?) decreasing as MgO decreases. Microprobe analyses of olivine and chromite from the three basaltic samples show that both chromite and olivine became more iron rich during fractionation. Olivine compositions decrease from Foss.2 to Foss.1 as MgO in the whole rock decreases from 14.7 to 8.8 wt%. The dredged basalts differ from those drilled in Hole 317A on the High Plateau by containing olivine, chromite, and pigeonite, and at the same time having higher SiO2 concentrations. The dredged basalts and their phenocryst-free glass compositions fall on olivine control lines, as their mineralogy suggests they should. A liquid having the composition of the dredged basalts could be generated by a large degree of partial melting at very shallow mantle depths. Liquids with the general compositional range of the drilled Manihiki basalts are consistent with a somewhat smaller degree of partial melting at a somewhat greater depth. The gabbroic cumulate contains chromite (average) (Tio.06 Fe+20.06) (Mg3.14 Fe+24.79 Mno.08) (Cr10.78Al3.75Fe+31.38)O32, bronzite (average) (En80.4W05.5FS14.1), augite (Ens3.1 W038.5Fs8.4), saponite and serpentine pseudomorphs after subhedral to euhedral olivine, and rare labradorite and a Carich zeolite. The recovery of the gabbroic cumulate within the Danger Island Troughs suggests that at one time the troughs were the site of active faulting. A tectonic model for the evolution of the plateau, consistent with a fracture zone origin for the Danger Island Troughs, requires the formation of the Manihiki Plateau at a triple junction of the Pacific, Farallon, and Antarctic plates.

INTRODUCTION AND GEOLOGIC SETTING

Winterer et al. (1974), in describing the general structure and acoustic stratigraphy of the Manihiki Plateau, divided the plateau into three distinct morphologic subprovinces, the High, the North, and the Western plateaus. These subprovinces are separated from one another by deep internal troughs, the Western Plateau from the High Plateau by a system of en echelon northeast-trending troughs, the Danger Island Troughs (Mammerickx et al., 1974). Basement rocks crop out at many places on steep slopes along narrow ridges in the Western Plateau and within the Danger Island Troughs.

Basement rocks were dredged at four localities in the Danger Island Troughs during the SOUTHTOW-11 expedition of the Scripps Institution of Oceanography (see Figure 1 for locations). Dredge 68D (9°49.0'S, 164°44.0'W, 4800 m) sampled the western scarp of the Danger Island Troughs opposite the intersection of Suvarov Trough with the en echelon Danger Island Troughs on the eastern side of a basement ridge rising 1.8 km (sec) above the adjacent Western Plateau and 2.4 km (sec) above the Danger Island Troughs. Dredge 70D (10°00.0'S, 164°13.0'W, 4400 m) sampled a 0.6-km (sec) fault scarp bounding the western edge of the High Plateau. Airgun profiles show about 0.3 km (sec) of outcropping Cretaceous (?) sediments overlying 0.3 km (sec) of outcropping basement; the bottom 0.1 km (sec) of basement is concealed beneath slumped blocks of plateau sediments. Dredge 78D (8°40.9'S, 163°42.7'W, 4085 m) sampled the west wall of the Danger Island Troughs on a scarp of a basement high (vertical relief 1.5 km [sec]) that rims the Western Plateau. Dredge 80D (7°59.0'S, 163°42.0'W, 4700 m) sampled the eastern scarp of the Danger Island Troughs, a basement ridge that rises 2.2 km (sec) above the adjacent Danger Island



Figure 1. Bathymetric chart of the Manihiki Plateau (from Winterer et al., 1974), contour interval, 200 meters. Dredge location shown by dots. Exact location and depth of dredges given in text.

Troughs. Dredges 68D, 78D, and 80D were all taken on basement ridges; dredge 70D was taken in an attempt to recover sedimentary and basement rocks from the fault bounding the High Plateau. Airgun profiles near each dredge location, given by Winterer et al. (1974), show the approximate location of dredged scarps for dredges 68D, 70D, 78D, and 80D, respectively (their fig. 10e, 5d, 10d, and 10b). Hole 317A is near the center of the High Plateau, southeast of the dredge sites (Figure 1).

PETROGRAPHY OF DREDGED SAMPLES

The general petrography of the basalts and single gabbroic cumulate recovered is reported by Clague (quoted in Winterer et al., 1974). Dredge 68D recovered pale brown altered basalt and volcanic breccia cemented by phosphorite and coated by manganese (see Plate 1, Figure 1). Nearly all the basalt fragments recovered are altered to bright green montmorillonite-group clays on the margins. Fragments up to 3 cm in diameter are completely altered (see Plate 1, Figure 2). Dredge 70D recovered about 25 pebbles of very highly altered basalt and volcaniclastite; nearly all samples are nuclei of manganese nodules. Dredge 80D recovered a few small pebbles of very highly altered basalt and volcanic breccia. No thin sections were made of any samples from dredges 68D, 70D, or 80D, owing to the extreme alteration observable in hand specimens.

Dredge 78D recovered about 25 pebbles, the largest about 5 cm in diameter, nearly all highly altered variolitic basalt. A typical example contains about 15% iddingsite pseudomorphs after olivine phenocrysts set in a matrix of glass altered to montmorillonite-group clays, skeletal plagioclase laths, and subordinate clinopyroxene. In three of the samples, a white to pale green alteration rind of montmorillonite-group clays, 2 to 5 mm thick, surrounds fresh black prophyritic basalt (see Plate 2, Figures 3 and 4). Two of these samples (ST11-78-15; ST11-78-14) are petrographically identical and contain 15%-20% olivine phenocrysts; the third sample contains only rare olivine phenocrysts. The larger olivine crystals (up to 2mm) are deeply embayed by glass (see Plate 1, Figures 5 and 6); the smaller crystals (to 0.7 mm) are subhedral to euhedral. A few calcite pseudomorphs after olivine phenocrysts are present. These rocks contain abundant euhedral microphenocrysts (up to 0.07 mm) of dark red-brown chromite. Most of the chromite crystals are enclosed in olivine phenocrysts; a few clusters or single crystals occur in the glassy groundmass. The presence of spinel in clusters in the groundmass suggests that these chromite crystals may have been enclosed in olivine crystals that are now completely resorbed by glass. The groundmass is mainly dark brown to black glass that contains plumose quench pigeonite (see Plate 1, Figure 7) elongate grains of quench olivine (see Plate 1, Figure 8 and Plate 2, Figure 1), and, rarely, amygdules of calcite and chalcedony. The third fresh basalt sample (ST11-78-16) has a similar texture but contains only about 3% olivine phenocrysts (<0.9 mm) and rare plagioclase microphenocrysts. Chromite is much less abundant than in Samples ST11-78-15 or ST11-78-14. The quench pigeonite microlites, though still of unusual plumose texture, are better developed (<0.2 mm). The elongate skeletal quench olivine grains

are less abundant than in Samples ST11-78-15 or ST11-78-14. In all three samples, the altered rind is composed mainly of montmorillonite-group clays, and the olivine phenocrysts in the rind have altered to a colorless highly birefringent fibrous clay (probably nontronite or saponite).

The dredged basalts contain no vesicles, whereas the drilled basalts are highly vesicular. The absence of vesicles in the dredged basalts indicates that these basalts erupted in deep water, whereas the drilled basalts are interpreted by Jackson et al. (this volume) to have erupted in very shallow water. The petrology of the basalts drilled in Hole 317A is described by Jackson et al., (this volume). The dredged basalts differ by the presence of olivine, chromite, and pigeonite and the absence of microphenocrysts of plagioclase and pyroxene.

Dredge 78D recovered, in addition to the fresh olivine basalt (ST11-78-15 and ST11-78-14) and the olivinebearing basalt (ST11-78-16) described above, a single 1.5-cm-diameter pebble of highly altered gabbroic cumulate. The sample contains abundant subhedral to euhedral pseudomorphs of clay minerals and serpentine after olivine. In one part of the sample, pseudomorphs of serpentine having a bastite texture (see Plate 2, Figure 2) occur only a few mm away from highly birefringent, pleochroic, pale yellow to tan fibrous saponite replacing olivine (Mg-rich montmorillonite; see section entitled mineral compositions and Plate 2, Figures 3 and 4).

An X-ray diffractogram of the sample reveals only pyroxene, montmorillonite-group minerals (14.26Å), and serpentine (or septochlorite). Small remanent fragments of augite and hypersthene crystals are present, although both pyroxenes are extensively replaced by clays. The former presence of 20%-30% feldspar is inferred from the abundance of low-birefringent clays (montmorillonite-group minerals) and Ca-rich zeolites between mafic grains and the observed replacement of a single plagioclase feldspar lath by similar clays. Accessory euhedral chromite is abundant ($\sim 3\%$ of sample) and almost invariably occurs within or along the grain boundaries of olivine pseudomorphs. The textural association of chromite and olivine pseudomorphs (see Plate 2, Figures 3 and 4) supports the identification of the pseudomorphs as being secondary after olivine. Prior to alteration, the rock appears to have been an olivine-chromite cumulate; it contains post-cumulus bronzite, augite, and plagioclase.

CHEMICAL COMPOSITION OF DREDGED ROCKS

Major Elements

Samples ST11-78-14, -15, and -16 from dredge 78D were analyzed for major elements by X-ray fluorescence and atomic absorption spectrometry. SiO₂, Al₂O₃, FeO (total iron calculated as FeO), CaO, K₂O, TiO₂, and P_2O_5 were determined by X-ray fluorescence on polished La₂O₃-spiked LiBO₃ fused sample and standard discs; Na₂O, MgO, and MnO were determined by atomic absorption spectrometry. Sample preparation, instrumental operating conditions, corrections for spectral interferences, and precision and accuracy of the analyses

are given by Clague (1974). The analyses are presented in Table 1 along with normalized analyses and calculated CIPW norms. Sample ST11-78-14 was contaminated with styrene plastic from the Spex mixer mill used for pulverizing the sample. Chemical analysis of the contaminant indicates that the plastic does not contain detectable amounts of any of the analyzed elements and should be considered a dilutent only. The low total reported for this sample reflects the presence of a few percent of this plastic dilutent. The slightly low totals reported for ST11-78-15 and ST11-78-16 most probably reflect the presence of H_2O and CO_2 , which were not determined.

All three analyzed samples are hypersthene normative and highly depleted in K_2O , P_2O_5 , and TiO₂. Their classification as abyssal tholeiite (Engel et al., 1965) is unequivocal despite the high concentration of MgO in Samples ST11-78-15 and -14. Sample ST11-78-16 contains at least 1.17% normative quartz (calculated from the dry reduced analysis). All three analyzed basalts plot in the tholeiite field on a total alkali-silica diagram (Figure 2); all fall within the field of Site 317A basalts on a normative An-Ab-Or ternary diagram (see Figure 3a). On an AFM diagram (Figure 3b), sample ST11-78-16 falls within the field of Hole 317A basalts but Samples ST11-78-14 and -15 are far more MgO rich due to the abundance of olivine than any of the Hole 317A basalts. Plotted on a ternary normative Ol-Hy-Di-Qtz diagram, the dredged basalts bracket the field of Hole 317A basalts. Samples ST11-78-14 and -15 are more olivine normative than any of the drilled basalts, again reflecting the abundance of olivine phenocrysts. Sample ST11-78-16 is quartz normative, which reflects the low abundance of olivine phenocrysts and the high SiO₂ content of the rock.

A direct comparison of the analyses of basalts dredged from the Danger Island Troughs with those cored in Hole 317A shows that the dredged basalts are richer in SiO₂ and poorer in Al₂O₃, TiO₂, and P₂O₅. The concentrations for all other major elements are overlapping. The major element chemical variations are shown diagrammatically on MgO variation diagrams of Fig-

 TABLE 1

 Chemical Analyses^a of Lavas Dredged From the Manihiki Plateau

	1	ST11-78-15			ST-11-78-14			ST11-78-16	
Major Element Analyses	Analysis as Received	Analysis N to 10 ("Dry Ar	Analysis Normalized to 100% ("Dry Analysis")		Analysis M to 1 ("Dry A	Vormalized 00% nalysis")	Analysis as Received	Anlaysis Normalized to 100% ("Dry Analysis")	
SiO ₂	49.77	50.84	50.75	49.19	51.27	51.19	52.03	52.92	52.84
Al ₂ Õ ₃	11.60	11.85	11.83	11.90	12.40	12.38	13.80	14.04	14.01
Fe ₂ O ₂	-	-	1.67 ^c	-	-	1.58 ^c	-	-	1.65 ^c
FeO	9.70 ^b	9.91 ^b	8.38 ^c	9.00 ^b	9.38 ^b	7.94 ^c	9.54 ^b	9.70 ^b	8.21 ^c
MgO	14.40	14.71	14.68	13.30	13.86	13.84	8.65	8.80	8.78
CaO	9.87	10.08	10.07	9.95	10.37	10.35	11.20	11.39	11.37
NapO	1.81	1.85	1.85	1.76	1.83	1.83	1.98	2.01	2.01
K ₂ O	0.12	0.12	0.12	0.23	0.24	0.24	0.23	0.23	0.23
TiO	0.46	0.47	0.47	0.47	0.49	0.49	0.71	0.72	0.72
PoOs	0.03	0.03	0.03	0.01	0.01	0.01	0.03	0.03	0.03
MnO	0.14	0.14	0.14	0.14	0.15	0.15	0.14	0.14	0.14
Total	98.30 ^d	100.00	99.99	96.27 ^{de}	100.00	100.01	98.48 ^d	99.98	99.99
CIPW Norm									
q		_						1.17	3.03
or		0.72	0.72		1.42	1.41		1.38	1.38
ab		15.64	15.62		15.52	15.50		17.04	17.01
an		23.67	23.63		24.90	24.86		28.57	28.52
wo		10.92	10.90		11.06	11.04		11.59	11.57
ai f en		6.90	7.35		6.99	7.45		6.31	6.92
(en		3.33	17.02		5.56	18 52		4.80	14.04
hy fs		7.00	6.61		7 34	6.84		12.03	8 74
fo		10.68	7.92		8.65	5.96		0.00	0.00
ol j fa		5.68	3.22		4.61	2.43		0.00	0.00
mt		0.00	2.42		0.00	2.29		0.00	2.38
il		0.89	0.89		0.93	0.93		1.37	1.37
ap		0.07	0.07		0.03	0.03		0.07	0.07

^aD.A. Clague, analyst.

^bAll iron as FeO.

^cFeO and Fe₂O₃ adjusted so that FeO/Fe₂O₃ = 5.

^dTotal includes NiO and Cr₂O₃.

^eTotal is low due to contamination by plastic during grinding and pulverizing.



Figure 2. Total alkali: silica diagram (after Macdonald and Katsura, 1964) for dredged (dredge ST11-78D) basalts from Danger Island Troughs and basalts drilled at DSDP Hole 317A (Field B; Jackson et al., this volume) and Site 289 (Field A; Stoeser, in press). Samples ST11-78-15-1, ST11-78-14-2, and ST11-78-16-3, Glass ST11-78-15-7, Glass ST11-78-14-4, Glass ST11-78-16-9.

ure 4. The fields for basalts from Site 317 (Jackson et al., this volume) and the Ontong-Java Plateau (Stoeser, in press) are shown for comparison.

Partial analyses of the glass (including both quench pigeonite and olivine but excluding chromite and olivine phenocrysts) were determined by electron microprobe using a 10µ-diameter beam (Table 2). The glass compositions for Samples ST11-78-14, -15, and -16 show considerably less MgO than the whole-rock compositions. Considered alone, the dredged basalts and the basalt glass from the same samples fall on an olivine control line (see Wright, 1971, and Figure 4) as their mineralogy suggests they should. It is not certain whether the whole-rock and glass compositions are related by fractional crystallization of olivine and chromite or by the incorporation of variable amounts of olivine and chromite xenocrysts during ascent of the magma. The embayed crystal forms of most of the olivine phenocrysts suggest that the crystals are xenocrysts rather than phenocrysts.

The chemical relation of the dredged basalts to the Hole 317A basalts is less clear. The high silica content of the dredged basalts, particularly the basaltic glasses, relative to those in the drilled basalts, together with the presence of both phenocryst and quench olivine in the dredged basalts and its absence from the drilled basalts, appears to be a paradox. It is clear that the dredged and drilled basalts cannot be related by shallow fractionation of olivine, clinopyroxene, or plagioclase or any combination of these minerals; the differences in composition are perhaps better ascribed to differences in temperature, depth or volume of melting, or possibly to differences in parental materials.

Minor Elements

Cr, Nb, Ni, Zr, Y, Sc, and Ba were determined by quantitative spectrochemical analysis using methods



Figure 3. An-Ab-Or, A-F-M, OL-DI-HY-QTZ ternary diagrams (after Irvine and Baragar, 1971) for dredged (dredge ST11-78D) basalts from Danger Island Troughs, basalt recovered at DSDP Hole 317A (Field B; Jackson et al., this volume) and Site 389 (Field A; Stoeser, in press). Sample identification for dredged basalts and phenocryst-free glass compositions given in caption to Figure 2.





Figure 4. MgO variation diagrams for dry, reduced oxides of basalts dredged (dredge ST11-78D) from Danger Island Troughs and basalt drilled at DSDP Hole 317A (Field B; Jackson et al., this volume) and Site 289 (Field A; Stoeser, in press). Lines marked of project to olivine of composition Fo85 and show olivine control of dredged samples. Sample identification for dredged basalts and phenocryst-free glass compositions given in caption to Figure 2.

Microprobe	Analyses of Phe	enocryst-Free Ba	asaltic Glass
	ST11-78-14	ST11-78-15	ST11-78-16
SiO ₂	53.6	53.5	53.7
Al ₂ O ₃	14.7	14.5	15.1
FeO	9.7	9.8	10.1
MgO	7.9	7.5	6.7
CaO	11.4	11.4	11.3
Na ₂ O	1.8	2.0	2.0
K ₂ O	0.2	0.2	0.2
TiO ₂	0.6	0.7	0.8
Total	99.9	99.5	99.9
CIPW Norms			
Q	3.93	3.57	4.54
Or	1.18	1.19	1.18
Ab	15.25	16.99	16.94
An	31.47	30.12	31.66
En	5.50	5.71	4.94
Wo Di	10.50	11.13	10.21
Fs J	4.70	5.14	5.10
Enlu	14.20	13.05	11.76
Fs ∫ ^{ny}	12.14	11.76	12.14
11	1.14	1.33	1.52

TABLE 2

described by Bastron et al. (1960); Sr, Cu, Rb, and Zn were determined by atomic absorption spectrometry using a heated graphite analyzer. Sample preparation, ab-

sorption lines employed, and drying, charring, and atomizing times and temperatures for the graphite furnace are described by Clague (1974). The determination of Co, V, Cu, and Zn may not truly reflect the wholerock concentrations due to the failure to totally dissolve chromite using the methods employed. V, in particular, may be highly concentrated in chromite (E.D. Jackson, personal communication, 1974), and the values reported may be low. The minor-element data are listed in Table 3 with the range and average value for each element in oceanic tholeiitic basalt compiled by Jackson et al. (this volume) from various sources. The trace-element data clearly show that the basalts are strongly depleted in the compatible trace elements Ba, Sr, Rb, Zr, Pb, Nb (?), and Y, as well as K₂O, P₂O₅, and TiO₂. The high Nb concentrations reported for Samples ST11-78-14 and ST11-78-15 could be due to contamination from the tungsten carbide grinding balls and end-caps in the Spex swing mill used for grinding the samples, as tungsten carbide may contain a significant amount of Nb (B. Fabbi, oral communication, 1975). It is likelier, however, that the high values reflect the substitution of Nb into chromite and that the concentrations reported are correct.

The concentrations of Cr, Ni, Co, and Sc are higher than previously reported for abyssal tholeiites. It is apparent from Table 15 of Jackson et al. (this volume) that the basalts from Hole 317A are depleted in the same incompatible trace elements as the dredged basalts, but to

TABLE 3 Minor Element Concentrations (ppm)

	ST11	ST11	ST11-	Oceanic- Tholei	Ridge ite
	78-15	78-14	78-16	Range ^a	Average ^a
Bab	14	16	32	2-180	25
Sr ^C	50	30	40	70-440	199
Cod	120	115	70	6-75	42
Crb	2500	2000	1100	70-700	320
Cu ^c	81	89	99	10-700	148
Nb ^b	90	120	N20	1.9-88	14
Ni ^b	550	440	200	15-500	149
Pe	131	44	131	131-2226	865
Scb	70	100	60	30-70	51
Tie	2818	2938	4316	3537-17086	9452
Vd	275	240	315	150-440	246
Yb	28	32	26	15-100	37
Zrb	N20	N20	N20	15-950	137
Rb ^c	<1	<1	2	-	1.1 ^f
Pbd	<1	<1	3		0.8 ^g
Zn ^c	93	94	122		$\sim - 1$

^aData for range and average compiled by Jackson et al., this volume, except for Rb and Pb.

^bQuantitative spectrographic analyses, Robert Mays, analyst; Brant Fabbi, Project Leader (Acting). N20 = not detected at 20 ppm.

^cAtomic absorption analyses, Sr and Zn by method of additions; David Clague, analyst.

^dAtomic absorption analyses using heated graphite furnace; David Clague, analyst.

^eX-ray fluorescence analyses; David Clague, analyst.

^fAverage Rb value from Hart (1971).

gAverage Pb value from Tatsumoto et al. (1965).

a lesser extent. The 317A basalts are slightly enriched in Cr and Co but slightly depleted in Ni and Sc relative to the average concentrations of these elements in abyssal tholeiites. The dredged and drilled basalts show some trace-element affinities but not in a direction compatible with a simple fractionation relation.

The Cr and Ni concentrations have been plotted as a function of MgO content (Figures 5 and 6), Sample ST11-78-16 has about twice the concentrations of both Ni and Cr as those of the Hole 317A basalts with similar MgO content. The plot of Ni relative to MgO shows that the Ni concentration of the Hole 317A basalts is relatively constant; this suggests that olivine is not a major crystallizing phase in basalts with MgO <10% during shallow fractionation, as proposed by Kay et al. (1970). The high concentrations of Ni and Cr, together with the textural evidence, suggests that most, if not all, phenocryst olivine and chromite in Samples ST11-78-14, -15, and -16 occur as xenocrysts. This interpretation would explain the highly embayed crystal forms as well as the unusually high Ni and Cr content of Sample ST11-78-16, a basalt containing <9% MgO and >52% SiO2.

The dredged basalts plot closer to the origin on a P_2O_5 -TiO₂ diagram (Figure 7) than any basalt in the abyssal tholeiite field of Bass et al. (1973) or from Hole 317A. On a plot of Zr relative to Nb, the dredged lavas



Figure 5. Ni:MgO diagram comparing basalts dredged (dredge ST11-78D) from Danger Island Troughs with basalt drilled at DSDP Site 317A (Jackson et al., this volume).

are strongly depleted with respect to Zr, but the Nb values are highly variable. Plots of Zr relative to Sr (Figure 8) show that the dredged basalts are more depleted in both elements than either the Hole 317A basalts or the abyssal tholeiites used by Bass et al. (1973) to determine the field for ocean-ridge basalts. Pearce and Cann (1973) suggested several trace-element plots to be employed in classifying basalts. On their plot of Ti relative to Zr, the dredged basalts fall in the region of low-potassium island arc tholeiites rather than the ocean-ridge tholeiite field. Similarly, on a ternary plot of Ti/100, Zr and Y \cdot 3, the dredged basalts fall outside the boundaries of any field determined by Pearce and Cann (1973). The dredged basalt plots far into the Y \cdot 3 corner of such a diagram. Ishikawa (1968) used ternary plots of Co, V, and Ni (Figure 9) to determine fractional crystallization paths of both tholeiitic and alkalic basalts. Two of the dredged lavas (ST11-78-15, -14) plot towards the Ni corner (Figure 9), one (St11-78-16)



Figure 6. Cr:MgO diagram of basalts dredged (dredge ST11-78D) from Danger Island Troughs and basalt drilled at DSDP Hole 317A (Jackson et al., this volume).



Figure 7. P₂O5:TiO₂ diagram (after Bass et al., 1973) for basalts dredged (dredge ST11-78D) from Danger Island Troughs and basalt drilled at DSDP Hole 317A (Jackson et al., this volume). Fields for ocean-ridge tholeiite, ocean island tholeiite, and alkali basalt from Bass et al., 1973.



Figure 8. Zr:Sr diagram (after Hubbard, 1967; Bass et al., 1973) of basalts dredged (dredge ST11-78D) from Danger Island Troughs and basalt drilled at DSDP Hole 317A (Jackson et al., this volume). Fields for ocean-ridge tholeiite, ocean island tholeiite, and alkali basalt from Bass et al. (1973).

within the field of Hole 317A basalts. The high-MgO samples (ST-78-15, -14) are considerably richer in Co than the high-MgO basalt from the Ontong-Java Plateau described by Stoeser (in press). During fractionation, the trend observed on the Co, Ni, V ternary plot appears to roughly parallel a line of constant Co while moving from the Ni corner toward the V corner. The positive correlation of Ni with Mg and V with Fe suggests that the Co, V, Ni ternary plot closely resembles an AFM plot during early fractionation.

The close correlation of Sc (?), Co, Cr, and Ni suggests that these elements are rapidly depleted during

fractionation of olivine and chromite. Co+2 probably substitutes for Fe⁺² and Ni⁺² substitutes for Mg⁺² in olivine. Sc+3 apparently substitutes into chromite for Cr⁺³, Al⁺³, or Fe⁺³. During fractionation of the dredged basalts, Zn+2 increases from 93 to 122 ppm as MgO decreases from 14.7% to 8.8%. Zn is <20 ppm in all the Site 317 basalts, suggesting that Zn was removed from the liquid by crystallization of small amounts of sulfides. Cu increases from 81 to 99 ppm as MgO decreases from 14.7% to 8.8%. V increases from 240 to 315 ppm despite the crystallization of chromite, which may contain up to 0.5% V₂O₃ (E.D. Jackson, personal communication, 1974). Most of the "incompatible trace elements" (Green and Ringwood, 1967) increase from Samples ST11-78-15 and -14 to Sample ST11-78-16 (as MgO decreases). In particular, Ba, Rb, and Rb more than double while Sr, Y, and Zr remain relatively constant.

Mineral Analyses

Electron microprobe analyses of phenocrysts and microphenocrysts of olivine and chromite from Samples ST11-78-14, -15, and -16 are given in Tables 4 and 5. All mineral analyses were performed using a focused beam approximately 2μ in diameter. FeO and Fe₂O₃ were calculated for the chromite analyses assuming perfect spinel stoichiometry ($R^{+2}=R^{+3}+Ti$). The four analyzed olivine phenocrysts in ST11-78-15 average Foss, and have a range of FO87.7 to FO88.4. The two phenocrysts with the lower Fo content are large embayed olivine phenocrysts; phenocrysts (01-15-3 and 15-4) having the higher Fo content are smaller euhedral olivine. The cromite grains which coexist with these olivine phenocrysts show considerable chemical variation, particularly in the ratio Cr/(Cr+Al), which ranges from 0.685 to 0.736 for three chromite grains analyzed from Sample ST11-78-15. The largest chromite crystal has the lowest concentration of Cr2O3. Sample ST11-78-14 contains olivine phenocrysts (average Foss2) with composition identical to those in ST11-78-15. The analyzed chromite grains show an even larger compositional variation than those from ST11-78-15; the ratio Cr/(Cr+Al) ranges from 0.701 to 0.776. Whereas compositions of both olivine and chromite from Samples ST-78-15 and -14 are nearly identical, Sample ST11-78-16 contains olivine phenocrysts with an average composition Fo85.1 and chromite with Cr/(Cr+Al) averaging 0.679. The chromite from ST11-78-16 is much richer in TiO2, FeO, and Fe2O3, but contains considerably less Cr2O3. The whole-rock chemistry indicates that ST11-78-16 is more fractionated or contains fewer olivine xenocrysts than either ST11-78-15 or -14. The mineral analyses of olivine phenocrysts from these three samples confirm this interpretation, as the olivine from ST11-78-16 is more iron rich than that from ST11-78-15 or -14. Chromite compositions change during fractionation as the variations between ST11-78-16 chromite and ST11-78-14 or -15 chromite show.

Jackson (1969) and Evans and Wright (1972) have shown that the ratio $Fe^{+2}/(Fe^{+2}+Mg)$ in chromite and olivine covary. From the relationship between $Fe^{+2}/(Fe^{+2}+Mg)$ in olivine and in chromite from the Manihiki dredged basalts and the Makaopuhi lava lake shown in Figure 10, it is apparent that the chromite which coexists with olivine in the Manihiki basalts has a considerably higher ratio of $Fe^{+2}/(Fe^{+2}+Mg)$ than



Figure 9. Co-V-Ni ternary diagram after Ishikawa (1968) of basalts dredged (dredge ST11-78D) from Danger Island Troughs and basalt drilled at DSDP Hole 317A (Jackson et al., this volume) and Site 389 (Stoeser, in press).

											-				
	ST11-78 -16-1A	ST11-78 -16-1B	ST11-78 -16-2	ST11-78 -16-3	ST11-78 -16-4	ST11-78 -15-1	ST11-78 -15-2	ST11-78 -15-3	ST11-78 -15-4	ST11-78 -14-1	ST11-78 -14-3	ST11-78 -14-4	Average ST11-78 -16	Average ST11-78 -15	Average ST11-78 -14
SiO ₂	39.3	39.9	40.5	40.9	40.6	40.55	40.7	40.8	40.65	40.3	41.0	41.0	40.24	40.69	40.77
FeO	14.0	14.1	14.1	14.45	14.2	11.5	11.8	11.0	11.0	11.1	11.7	11.3	14.17	11.32	11.37
MgO	44.6	45.2	45.85	45.7	45.4	46.7	47.3	47.3	47.25	47.0	47.3	47.9	45.32	47.15	47.40
TiO ₂	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.00
CaO	0.24	0.24	0.27	0.24	0.27	0.23	0.24	0.21	0.22	0.24	0.26	0.28	0.25	0.22	0.26
Al ₂ O ₃	0.06	0.06	0.09	0.09	0.07	0.06	0.09	0.08	0.16	0.07	0.06	0.08	0.07	0.10	0.07
MnO	0.24	0.24	0.22	0.22	0.23	0.17	0.19	0.19	0.16	0.20	0.20	0.20	0.23	0.17	0.20
Na ₂ O	0.03	0.03	0.02	0.00	0.10	0.02	0.01	0.01	0.01	0.00	0.01	0.00	0.03	0.01	0.00
Total	98.49	99.79	101.06	101.62	100.88	99.24	100.34	99.59	99.46	98.92	100.53	100.76	100.33	99.67	100.07
							Cations Per	4 Oxygens							
Si	0.999	1.000	1.002	1.006	1.006	1.008	1.003	1.008	1.001	1.004	1.007	1.003	1.003	1.005	1.005
Fe	0.297	0.296	0.292	0.297	0.294	0.239	0.243	0.227	0.226	0.232	0.240	0.231	0.295	0.234	0.234
Mg	1.689	1.689	1.689	1.675	1.675	1.732	1.736	1.742	1.734	1.746	1.732	1.747	1.683	1.736	1.742
Mn	0.005	0.005	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.004	0.004
ΣVI	1.991	1.990	1.986	1.977	1.974	1.975	1.983	1.973	1.964	1.982	1.976	1.982	1.983	1.974	1.980
$\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}}$	85.0	85.1	85.3	84.9	85.1	87.8	87.7	88.4	88.4	88.3	87.8	88.3	85.1	88.1	88.2

TABLE 4	
Chemical Composition and Structural Formula for Olivine Phenocrysts from Basalts Dredged from the Manih	iki Plateau

	ST11-	78D-16		ST11-78D-1	5		ST11-	78D-14		Average Compositions of ST11-78D Chromite		
	16-1	16-2	15-1	15-2	15-3	14-1	14-2	14-3	14-4	16	15	14
Cr2O3	45.3	45.5	49.6	52.8	51.0	50.0	50.8	52.3	56.3	45.4	51.1	52.3
Al ₂ O ₃	14.1	14.7	15.3	12.7	14.0	14.3	14.2	13.6	10.9	14.4	14.0	13.2
Fe ₂ O ₃ ^a	7.9	8.3	3.2	5.0	5.7	4.2	4.3	4.0	3.3	8.1	4.6	3.9
FeOa	17.2	17.0	15.3	16.0	15.3	16.2	15.6	15.9	16.1	17.1	15.5	16.0
MgO	10.3	10.6	11.4	11.3	11.9	10.9	11.4	11.3	10.9	10.45	11.5	11.1
MnO	0.29	0.30	0.34	0.34	0.31	0.32	0.33	0.34	0.36	0.29	0.33	0.34
TiO ₂	0.71	0.64	0.24	0.27	0.34	0.38	0.34	0.27	0.27	0.67	0.28	0.32
Total	95.70	97.04	95.28	98.41	98.55	96.30	96.97	97.61	98.13	96.38	97.39	97.25
					Cations Per	32 Oxygens						
Cr	9.67	9.55	10.48	10.98	10.49	10.55	10.62	10.89	11.85	9.60	10.65	10.98
Al	4.49	4.60	4.82	3.94	4.29	4.50	4.42	4.23	3.42	4.54	4.34	4.14
Fe ⁺³	1.60	1.66	0.64	0.99	1.12	0.84	0.86	0.79	0.66	1.64	0.92	0.79
Fe ⁺²	3.86	3.77	3.42	3.52	3.33	3.61	3.45	3.51	3.58	3.82	3.43	3.54
Mg	4.14	3.19	4.50	4.43	4.62	4.33	4.49	4.44	4.33	4.17	4.52	4.40
Mn	0.066	0.067	0.077	0.076	0.068	0.072	0.074	0.076	0.081	0.066	0.074	0.076
Ti	0.144	0.128	0.048	0.053	0.066	0.076	0.068	0.054	0.054	0.137	0.055	0.064
ΣR^{+3} +Ti	15.904	15.938	15.988	15.963	15.966	15.966	15.968	15.964	15.984	15.917	15.965	15.974
ΣR^{+2}	8.071	8.035	7.995	8.027	8.013	8.020	8.016	8.027	7.992	8.055	8.017	8.016
Cr/(Cr+Al+Fe ⁺³)	0.6135	0.6041	0.6574	0.6903	0.6598	0.6639	0.6679	0.6843	0.7438	0.6084	0.6695	0.6904
$Fe^{+3}/(Cr+Al+Fe^{+3})$	0.1018	0.1049	0.0404	0.0622	0.0702	0.0531	0.0538	0.0499	0.0415	0.1039	0.0578	0.0495
Al/(Cr+Al+Fe ⁺³)	0.2847	0.2910	0.3023	0.2475	0.2700	0.2830	0.2783	0.2658	0.2147	0.2877	0.2727	0.2601
Cr/(Cr+Al)	0.6831	0.6749	0.6850	0.7361	0.7096	0.7011	0.7059	0.7203	0.7760	0.6790	0.7106	0.7263
Mg/(Mg+Fe ⁺²)	0.5177	0.5264	0.5683	0.5571	0.5809	0.5453	0.5657	0.5588	0.5468	0.5223	0.5688	0.5539

0,50

TABLE 5 Chemical Composition and Structural Formula for Chromite from Basalts Dredged From the Manihiki Plateau

^aFeO and Fe₂O₃ calculated assuming ideal spinel stoichiometry with RO = R_2O_3 .

chromite from Kilauea Iki (Evans and Wright, 1972) coexisting with olivine of similar composition. Jackson (1969) derived an equation to calculate nominal crystallization temperatures from olivine-chromite pairs assuming the pairs were demonstrably crystallized at a cotectic boundary and that the spinel solid solutions were ideal (Eq. 1)

 $T(^{\circ}K)$

$$= \frac{5580\gamma + 1018\beta - 1720\delta + 2400}{0.90\gamma + 2.56\beta - 2.08\delta - 1.47 + 1.987 \ln K_{D_{Mg} - Fe^{+2}}}$$

where $K_{D_{Mg} - Fe^{+}} = \frac{X_{Mg}^{OL} X_{Fe^{+2}}^{CHR}}{\frac{OL}{X_{Fe^{+2}} X_{Mg}^{CHR}}}$

and γ , β , and δ are given by

(Mg, Fe⁺²) (Cr α Al β Fe⁺³ δ)₂O₄. The temperatures derived using this expression for each possible equilibrated olivine-chromite pair (Table 6) are much too high, exceeding probably eruption temperatures by 400° to 700°C. Evans and Wright (1962) calculated similar high temperatures for olivine-chromite pairs from the Kilauea Iki and Makaopuhi lava lakes, concluding that Jackson's equation was not reliable to calculate temperatures of formation for terrestrial volcanic rocks because of several factors. In particular, they noted that uncertainty in calculating FeO and Fe₂O₃ from ideal



Figure 10. $Fe^{+2}/(Fe^{+2}+Mg)$ chromite: $Fe^{+2}/(Fe^{+2}+Mg)$ olivine diagram for olivine-chromite pairs in basalts dredged (dredge ST11-78D) from Danger Island Troughs. Range and average compositions for olivine (Table 4) and chromite (Table 5) are plotted. Chemical compositions of olivine-chromite pairs from Kilauea Iki basalt (Evans and Wright, 1972) are shown for comparison.

spinel stoichiometry could lead to relatively large errors, that the activity of TiO_2 must be considered due to the high TiO_2 content of chromite from Kilaeua Iki and

Chromite			C	livine			
Sample	16-1A	16-1B	16-2	16-3	16-4	16-Avg.	
16-1	1850°C	1835	1813	1858	1835	1835	Average: 1853°C
16-2	1879	1871	1840	1894	1871	1871	Range: 1813° - 1894°C
16-Avg.	1864	1853	1826	1876	1853	1853°C	
	15-1	15-2	15-3	15-4	15-Avg.		
15-1	1728°C	1741	1660	1660	1697	Average:	1775°C
15-2	1802	1829	1743	1743	1782	Range: 1	1660° – 1916°C
15-3	1901	1916	1813	1813	1856	200000 NO - 244 AD 2 19	
15-Avg.	1816	1823	1736	1736	1775°C		
	14-1	14-3	14-4	14-Avg.			
14-1	1615°C	1667	1615	1632		Average:	1727°C
14-2	1722	1780	1722	1741		Range: 1	1615° – 1839°C
14-3	1714	1778	1714	1733		0	
14-4	1780	1839	1780	1800			
14-Avg.	1708	1766	1708	1727°C			

TABLE 6
Calculated Nominal Temperatures (°C) for Olivine-Chromite
Pairs in Manihiki Dredged Tholeiitic Basalts

Makaopuhi lava lakes, and that Jackson's expression might be incorrect because of nonideality of the system. The high temperatures calculated for the very low-TiO₂ chromite-olivine pairs from the Manihiki Plateau Samples ST11-78-14 and -15 indicate that, while the activity of TiO₂ may cause errors, the high calculated temperatures from volcanic olivine-chromite pairs cannot be attributed to neglect of TiO2 in the thermodynamic derivation of Jackson's expression. A fourth possible explanation for the high calculated temperatures is that the olivine-chromite pairs in volcanic rocks do not represent equilibrium pairs since the chromite crystals are almost always enclosed in, and therefore predate, the olivine crystals. Jackson's expression is extremely sensitive to the forsterite content of the olivine, resulting in an increase of nearly 50°C for each 0.5 wt % decrease in forsterite content, calculated using a constant chromite composition. It is possible that the olivine and chromite compositions in the basalts may represent inherited olivine and chromite which have been unequally equilibrated.

Microprobe analyses of quench olivine from the three samples (Table 7) show that the phenocryst and quench olivine in Sample ST11-78-16 are nearly identical, whereas the quench olivine in Samples ST11-78-15 and -14 has a variable composition but is more iron rich than the phenocrysts. These relations suggest that the olivine phenocrysts in Sample ST11-78-16 are in equilibrium with the glass while those in the olivine-rich samples are not. The apparent disequilibrium of the olivine phenocrysts with the melt would seem to indicate that the inherited olivine and chromite may indeed be unequally equilibrated as suggested above.

The extremely fine grain size of the quench pyroxene in the dredged basalt samples makes microprobe analysis difficult. Table 7 lists a single analysis; the rest of the grains analyzed gave compositions approaching the glass compositions given in Table 2. The analyzed grain is a magnesian pigeonite as are the two grains for which only Ca, Fe, and Mg could be determined. These with the field for chromite from alpine peridotites. The Manihiki Plateau chromite data are close to the field of chromite from Kilauea Iki lava lake, though distinct from it. The chromite grains from Kilauea Iki are higher in Fe_2O_3 and lower in Cr_2O_3 than any of the chromite analyzed from the Manihiki Plateau samples.

The clinopyroxene from the gabbroic cumulate (Table 9) is augite, having an average composition $W_{038.5}En_{53.1}F_{58.4}$ and a range of compositions given by $W_{036.5-39.9}En_{54.8-52.1}F_{57.6-10.5}$. Individual crystals show nearly the entire rnage of compositions, being zoned with Fe-rich, Al-poor rims and Al-rich, Fe-poor centers. The orthopyroxene (Table 9) is bronzite, having an average composition $W_{03.5}En_{80.4}F_{514.1}$ and a range of compositions given by $W_{04.9-7.3}En_{83.2-78.2}F_{511.7-25.8}$. The rather high content of CaO in the bronzite crystals is almost certainly due to exsolution lamellae of clinopyroxene. These analyses and eight additional partial analyses are plotted in the pyroxene quadrilateral of Figure 11.

Distribution of Mg and Fe between coexisting orthopyroxene and clinopyroxene from sample ST11-78-23 yields an average D value of 1.13 where

$$K_D = \frac{X_{Fe}^{OPX} \ X_{Mg}^{CPX}}{X_{Mg}^{OPX} \ X_{Fe}^{CPX}}$$

(Kretz, 1961, 1964). Although the distribution coefficient has not been calibrated by laboratory experiment, Kretz (1961, 1964) has shown that pyroxenes crystallizing from mafic lavas have D values of about 1.4, and pyroxenes from crustal metamorphic rocks, values of about 1.8. The D value for Sample ST11-78-23 therefore indicates a high temperature of formation.

The pyroxene compositions are slightly enriched in iron and suggest that the sample corresponds to the upper part of layer 3. Microprobe analyses by Jackson et al. (1975) of pyroxenes from the Vourinos Ophiolite in Greece show that compositions of clinopyroxene simi-

TABLE 7	
Chemical Composition and Structural Formula of Quench Olivine and Pyroxene From Dr	redged Tholeiitic Basalts

	Pigeonite ST11-78-16	ST11-78- 16-1Q	ST11-78- 16-2Q	ST11-78- 16-3Q	ST11-78- 16-4Q	Olivine ST11-78- 15-3Q	ST11-78- 15-4Q	ST11-78- 14-1Q	ST11-78- 14-2Q	ST11-78- 14-3Q
SiO ₂	54.2	39.65	39.6	39.2	39.4	39.9	39.3	39.4	40.2	39.4
Al203	1.75	N.D. ^a	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
FeO	9.2	15.6	15.0	15.6	15.1	14.4	13.3	13.5	12.65	12.8
MnO	N.D.	0.21	0.19	0.18	0.16	0.19	0.17	0.18	0.15	0.16
MgO	25.7	44.1	44.35	45.2	44.6	45.6	47.15	47.9	47.4	48.35
CaO	6.5	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Total	97.35	99.56	99.14	100.18	99.26	100.09	99.92	100.88	100.40	100.71
Si	1.98	1.00	1.00	0.99	1.00	1.00	0.98	0.975	0.99	0.97
AllV	.02		-	-	_			-	_	-
AlVI	.06	-	-	-		-		=	-	-
Mg	1.40	1.66	1.67	1.70	1.68	1.70	1.75	1.77	1.75	1.78
Fe	.28	0.33	0.32	0.33	0.32	0.30	0.28	0.28	0.26	0.26
Ca	.25			2000-800 1977	7.55		1	$\overline{\mathcal{H}}$	-	-
$100 \text{ Mg/(Mg+Fe^{+2})}$	-	83.4	84.0	83.8	84.0	85.0	86.3	86.3	87.0	87.1
Ca	13.1				G 	-		-	-	-
Mg	72.3	-	-	-	-	-	—		-	-
Fe	14.5	-	-	-	-	-	-	-	-	:
ΣΥΪ	1.99	1.99	1.99	2.03	2.00	2.00	2.04	2.05	2:01	2.04

^aN.D. = not determined.

analyses are plotted in the pyroxene quadrilateral in Figure 11. The quench pigeonite is not chemically similar to any of the pyroxenes analyzed from the Hole 317A basalts (Table 12; Jackson et al., this volume).

Chromite from the gabbroic cumulate (Table 8) is somewhat more iron-rich and magnesium-poor than the chromite from Samples ST11-78-14, -15, and -16. The chromite analyses (Tables 5 and 8) demonstrate that the chromite from the cumulate is chemically distinct from the chromite of either the olivine basalt (ST11-78-14, -15) or the basalt (ST11-78-16). The color change in chromite from red-brown to dark red-brown to opaque does not correlate with increasing Cr_2O_3 but instead with increasing iron.

Much of the chemical variation observed among chromite grains from a single sample or single outcrop can be attributed to systematic variations in Cr/ (Cr+Al) and Mg/(Mg+Fe⁺²). All the chromite analyses from ST11-78-14, -15, -16, and -23 (Tables 5 and 8) have been plotted on a Cr/(Cr+Al) relative to $Mg/(Mg+Fe^{+2})$ diagram (Figure 12). The chromite grains analyzed fall within a restricted field compared lar to those in Sample ST11-78-23 occur only in the upper 500 meters of the layered sequence, and that similar orthopyroxene compositions occur much deeper in the layered sequence. Clinopyroxene compositions from the Papuan Ultramafic Belt (England and Davies, 1973) are all considerably more calcic than those from Sample ST11-78-23, orthopyroxene compositions as iron rich as those from Sample ST11-78-23 occur only in the gabbroic and ultramafic cumulates.

The classification of Sample ST11-78-23 as a gabbroic cumulate is highly dependent on identification of a single grain of labradorite ($\sim An_{66}$, calculated from content of CaO = 14.8%) and the presence of abundant colorless montmorillonite-group clays and fibrous zeo-

lites. A single partial analysis of one of the radiating fibrous zeolites (Table 10) confirms the zeolites as secondary after plagioclase, as they contain high concentrations of both CaO and Al_2O_3 and low concentrations of FeO and MgO (they are probably thomsonite or gismondine).

Most of the cumulus olivine has been replaced by a fibrous material, a small percentage by serpentine. The fibrous material has a chemical composition very similar to saponite (see Table 10 for four analyses), indicating that Al_2O_3 has been a fairly mobile component during alteration.

DISCUSSION

The basalts recovered in dredge ST11-78D from the Danger Island Troughs are abyssal tholeiite extremely depleted in many of the incompatible trace elements (P, Zr, Sr, Pb, Rb) and strongly enriched in MgO, Ni, and Cr. Petrographically, the samples are unusual in the high percentage of olivine phenocrysts and the presence of abundant chrome spinel and quench olivine. All samples contain quench clinopyroxene microlites exhibiting a striking plumose texture. Melson et al. (1975) have described other olivine-rich ridge tholeiites from the Mid-Atlantic Ridge.

The three analyzed dredge samples are quartz normative or strongly hypersthene normative, a composition indicating that the magmas equilibrated with wallrock at very shallow depths (pressures ≤ 5 kbar; Green and Ringwood, 1967). The high concentrations of MgO, Ni, and Cr in these basalts indicate that they have not undergone extensive or even minor shallow fractionation. As the composition of these basalts suggests equilibrium at shallow depths, the basaltic magma was probably generated by partial melting at shallow depths (pressures ≤ 5 kbar). The basalts drilled in Hole 317A,



- D ST11-78-23, full analysis from Table 9
- ST11-78-23, unpublished partial analysis
- STI1-78-16, quench clinopyroxene analysis from Table 7
- + ST11-78-16, quench clinopyroxene unpublished partial analyses

Figure 11. Pyroxene Ca-Mg-Fe ternary diagram showing compositions of bronzite and augite from Sample ST11-78-23 and the composition of quench Mg-pigeonite from Sample ST11-78-16.

TABLE 8 Chemical Compositions and Structural Formula for Chromite From Gabbroic Cumulate (ST11-78-23) Dredged From Manihiki Plateau

	23-1	23-2	23-3	23-4	23-5	23-6	Average
Cr ₂ O ₃	50.3	49.7	52.1	51.6	51.7	49.4	50.81
Al ₂ O ₃	11.4	12.1	11.8	11.5	11.6	12.8	11.86
Fe ₂ O ₃ ^a	7.4	7.8	6.2	7.2	5.9	6.5	6.84
FeOa	21.4	20.8	21.5	21.6	21.3	21.4	21.35
MgO	7.7	8.2	7.9	7.8	7.8	7.7	7.86
MnO	0.33	0.34	0.35	0.35	0.35	0.34	0.34
TiO ₂	0.34	0.31	0.28	0.25	0.26	0.25	0.28
Total	98.87	99.25	100.13	100.30	98.91	98.39	99.34
		Catio	ons Per 32 Ox	ygens			
Cr	10.75	10.52	10.97	10.88	11.03	10.54	10.78
Al	3.63	3.82	3.70	3.61	3.69	4.07	3.75
Fe ⁺³	1.51	1.57	1.24	1.44	1.20	1.32	1.38
Fe ⁺²	4.84	4.66	4.79	4.82	4.81	4.83	4.79
Mg	3.10	3.27	3.14	3.10	3.14	3.10	3.14
Mn	0.076	0.077	0.079	0.079	0.080	0.078	0.077
Ti	0.069	0.062	0.056	0.050	0.053	0.057	0.056
ΣR^{+3} +Ti	15.964	15.974	15.977	15.986	15.967	15.980	15.971
ΣR^{+2}	8.019	8.007	8.006	7.995	8.023	8.004	8.014
Cr/(Cr+Al+Fe ⁺³)	0.6767	0.6612	0.6892	0.6826	0.6930	0.6616	0.6775
$Fe^{+3}/(Cr+Al+Fe^{+3})$	0.0947	0.0988	0.0781	0.0906	0.0753	0.0829	0.0868
Al/(Cr+Al+Fe ⁺³)	0.2286	0.2400	0.2327	0.2268	0.2318	0.2555	0.2357
Cr/(Cr+Al)	0.7475	0.7337	0.7506	0.7506	0.7494	0.7214	0.7419
$Mg/(Mg+Fe^{+2})$	0.3907	0.4127	0.3916	0.3916	0.3949	0.3907	0.3962

^aFeO and Fe₂O₃ calculated assuming ideal spinel stoichiometry with RO = R_2O_3 .



Figure 12. Cr/(Cr+Al+Fe⁺³): Mg/(Mg+Fe⁺²) diagram for analyzed chromite grains (Tables 5 and 7). Hatchured zone includes data for 40 chromite grains from Kilauea Iki and Mokaopuhi lava lakes (Evans and Wright, 1972); data for dunite, harzburgite, chromitite, and orthopyroxenite are from the Burro Mountain (Loney et al., 1971), Vulcan Peak (Himmelberg and Loney, 1973) and Red Mountain-Del Puerto (Himmelberg and Coleman, 1968) alpine-type peridotites. Field enclosed by dashed lines includes chromite data from other alpine-type peridotites (Irvine, 1967).

which show comparable amounts of quartz and hypersthene in their norms, also appear to have been generated at shallow depths. The drilled basalts generally contain lesser amounts of the refractory elements than the dredged basalts and may be somewhat fractionated, assuming the parental meterials for the two basalt suites were the same. MacGregor (1969) demonstrated that the TiO₂ concentration of a eutectic melt in the system MgO-TiO₂-SiO₂ increases with pressure; he suggests that the TiO₂ content of basaltic liquids is a function of the depth at which partial melting occurs. The low TiO₂ concentrations of the dredged basalts, only about onefourth of average oceanic basalt concentrations (see Jackson et al., this volume) may indicate that the basaltic liquids were generated at shallow depths. The basalts drilled at Hole 317A have TiO2 concentrations about half the oceanic tholeiite averages; their TiO2 concentrations, interpreted in the same way as the dredged basalts, suggest deeper, but still shallow, depths of magma generation, again assuming the same parental material.

Hubbard (1969) demonstrated that a roughly inverse correlation exists between TiO2 and Al2O3 for oceanridge tholeiite, Hawaiian tholeiite, and Hawaiian alkalic basalt. He interpreted this correlation to indicate that Al₂O₃ decreases and TiO₂ increases in the basaltic liquid with increasing depth of magma generation. The dredged basalts are depleted in both Al₂O₃ and TiO₂, plotting far from the ocean-ridge tholeiite field of Hubbard (1969) on a plot of Al₂O₃ relative to TiO₂ (Figure 13). The basalts drilled in Hole 317A lie beneath Hubbard's field (1969), intermediate between its lower boundary and the dredged basalts. Green and Ringwood (1967) showed that higher degrees of partial melting tend to produce picritic magmas with low Al₂O₃ contents. The low concentration of Al₂O₃ in the Manihiki basalts may indicate a higher degree of partial melting. The low TiO₂ concentration could be due in part to magma generation at a shallow depth and in part to a large degree of partial melting. The correlation of Al₂O₃ and TiO₂ noted by Hubbard (1969) is consistent with shallow fractionation of plagioclase plus clinopyroxene resulting in high concentrations of Ti (and Fe) and low concentrations of Al₂O₃.

The extremely low concentrations of Sr, Zr, and P relative to concentrations found in "average" oceanridge tholeiite, can be interpreted as indicating a relatively large degree of partial melting for the Manihiki basalts (Gast, 1968).

Bass (1971) suggested that more rapidly spreading ridges generally tap magmas from lesser depths and that these ridges are underlain by a thinner lithosphere, the base of which he defines as the depth of brittle fracture. The chemistry of the Manihiki basalts in general, and the dredged basalts in particular, indicates a shallow magma source region for these rocks. This suggests that the ridge system at which the dredged basalts originated was fast spreading. Bass (1971) also suggested that magmas erupted at fast-spreading ridges generally undergo extensive low-pressure fractionation, perhaps in shallow, slowly cooling magma chambers in the lower crust as suggested by Cann (1970). The dredged basalts, as noted, have certainly not undergone extensive shallow fractionation, with the exception of Sample ST11-78-16, which can be interpreted as having lost olivine plus chromite. The failure of these basalts to equilibrate in shallow magma chambers and fractionate may result from a large degree of partial melting coupled with a shallow depth of magma generation. The basalts drilled in Hole 317A appear to have been derived from shallodepths, although they may be somewhat fractionated.

The Manihiki is a large area where tholeiitic basalts of the general ocean-ridge type erupted in shallow water (Jackson et al., this volume). The excessive volume of magma which erupted to form the Manihiki Plateau probably resulted from a shallowing of isotherms in this region that produced a large degree of mantle partial melting at very shallow mantle depths.

The recovery of a gabbroic olivine-chromite cumulate from a 1.5-km (sec) high basement outcrop in the

	OPX-23-1	OPX-23-4	OPX-23-9	OPX-23-12	OPX-23-8	CPX-23-2	CPX-23-3	CPX-23-13	CPX-23-14	CPX-23-15	CPX-23-16	CPX-23-21	Average OPX-23	Average CPX-23
SiO2	55.45	54.4	54.7	54.2	56.0	52.3	52.0	52.2	51.7	53.0	52.6	52.3	54.95	52.3
Al202	2.05	1.74	1.41	1.75	1.75	2.98	3.47	3.18	3.16	2.20	2.30	2.46	1.74	2.82
FeO	8.4	9.7	10.8	9.85	9.7	4.9	5.05	5.2	4.9	6.85	5.7	5.3	9.7	5.4
MnO	0.12	0.11	N.D.	N.D.	N.D.	0.08	0.08	N.D.	N.D.	N.D.	N.D.	N.D.	0.12	0.08
MgO	31.7	30.9	30.2	29.8	31.1	19.0	18.5	18.85	19.5	19.3	20.0	19.3	30.7	19.2
CaO	2.92	2.71	2.71	3.87	2.63	20.0	19.7	19.6	19.1	18.65	18.5	19.3	2.97	19.3
Na ₂ O	0.06	0.10	N.D.	N.D.	N.D.	0.17	0.19	N.D.	N.D.	N.D.	N.D.	N.D.	0.08	0.19
TiO ₂	0.08	0.17	N.D.	N.D.	N.D.	0.22	0.20	N.D.	N.D.	N.D.	N.D.	N.D.	0.14	0.21
Total	100.78	99.83	99.82	99.47	101.18								100.40	99.50
						C	ations Per 6 Oxyg	ens						
Si	1.93	1.93	1.94	1.93	1.95	1.91	1.91	1.91	1.91	1.93	1.93	1.93	1.94	1.92
AIIV	0.07	0.07	0.06	0.07	0.05	0.09	0.09	0.09	0.09	0.07	0.07	0.07	0.06	0.08
AIVI	0.01	0.00	0.00	0.00	0.02	0.04	0.06	0.05	0.05	0.02	0.03	0.04	0.01	0.04
Ti	0.00	0.00		-	-	0.01	0.01	-	-	-	-	-	0.00	0.01
Mg	1.65	1.63	1.60	1.58	1.61	1.03	1.01	1.03	1.07	1.05 2.01	1.09 2.02	1.06 2.02	1.61 2.01	1.05 2.02
Fe ⁺²	0.24	0.29	0.32	0.29	0.28 2.01	0.15	0.15	0.16	0.15	0.21	0.17	0.16	0.28	0.16
Mn	0.00	0.00	121	-	-	0.00	0.00	-		-	-	-	. 0.00	0.00
Ca	0.11	0.10	0.10	0.15	0.10	0.78	0.77	0.77	0.75	0.73	0.73	0.76	0.11	0.76
Na	0.00	0.00	-)	-)	-)	0.01	0.01	-)	-)	-)	-)	-)	0.00	0.01
Mg/Mg+Fe ⁺²	0.87	0.85	0.83	0.84	0.85	0.87	0.87	0.87	0.88	0.83	0.86	0.87	0.85	0.86
Ca)	5.4	5.1	5.1	7.3	4.9	39.8	39.9	39.3	38.2	36.7	36.4	38.4	5.5	38.5
Mg	82.3	80.7	79.1	78.2	81.0	52.6	52.1	52.6	54.2	52.8	54.8	53.4	80.4	53.1
Fe	12.2	14.2	15.8	14.5	14.2	7.6	8.0	8.1	7.6	10.5	8.8	8.2	14.1	8.4

 TABLE 9

 Chemical Composition and Structural Formula of Pyroxenes From the Dredged Gabbroic Cumulate (ST11-78-23)

^aN.D. = not determined.

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From the Dredged Gabbroic Cumulate (ST11-78-23)									
	ZEO-23-1	SAP-23-1	SAP-23-2	SAP-23-3	SAP-23-4	Thomsonite ^a	Saponite ^c	Saponite ^c	
SiO ₂	39.0	39.3	36.8	44.7	43.1	39.01	40.46	43.62	
Al203	29.3	5.8	8.6	4.4	4.8	29.94	10.15	5.50	
FeOb	0.7	10.5	9.8	8.0	7.6		8.09	0.59	
MgO	0.4	26.1	25.7	21.3	22.4	-	20.70	24.32	
CaO	13.1	0.3	0.5	0.7	0.7	12.71	1.94	2.85	
Na ₂ O	3.3 ^d	N.D. ^e	N.D.	N.D.	N.D.	4.80	0.25	0.08	
Total	85.8	82.0	81.4	79.1	78.6	99.70	100.23	100.03	
$\mathrm{H}_{2}\mathrm{O}^{\mathrm{f}}$	14.2	18.0	18.6	20.9	21.4	13.24	17.57	22.90	

TABLE 10 Partial Microprobe Analyses of Secondary Minerals From the Dredged Gabbroic Cumulate (ST11-78-23)

^aFrom Deer et al. (1963), v. 4, p. 367.

^bTotal iron calculated as FeO.

^cFrom Deer et al. (1963), v. 3, p. 234.

^dNa₂O in Sample ZEO-23-1 calculated assuming molecular ratio Al₂O₃: (Ca, Sr, Ba, Na₂, K₂)O equal to unity and assuming that SrO, BaO, and K₂O are negligible.

^eN.D. = not determined.

^fH₂O calculated by difference.



Figure 13. Al₂O₃:TiO₂ diagram (after Hubbard, 1969) of DSDP Hole 317A basalts (Jackson et al., this volume) and dredged basalts. Field shown encloses data from Hubbard (1969).

Danger Island Troughs suggests either that layer 2 is extremely thin beneath the Western Plateau or, more probably, that the Danger Island Troughs are a system of fracture zones (Melson and Thompson, 1971) containing fault slivers originating in layer 3. Only one of the two tectonic models presented by Winterer et al. (1974) for the generation of the plateau is consistent with the Danger Island Troughs being a fracture zone. This tectonic model, modified from that of Larson and Chase (1972), suggests that the plateau formed at a triple junction of the Pacific, Farallon, and Antarctic plates. Morgan (1972) and Wilson and Burke (1973) have noted that areas of voluminous mantle melting commonly are near lithospheric triple junctions. It appears from the interpretation developed here that the melting anomaly which produced the Manihiki Plateau may indeed have been a thermal anomaly.

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REFERENCES

- Bass, M.N., 1971. Variable abyssal basalt populations and their relation to sea-floor spreading rates: Earth Planet. Sci. Lett., v. 11, p. 18-22.
- Bass, M.N., Moberly, R., Rhodes, M.J., and Shih, C., 1973. Volcanic rocks cored in the central Pacific, Leg 17, Deep Sea Drilling Project. *In* Winterer, E.L., Ewing, J.I., et al., Initial Reports of the Deep Sea Drilling Project, Volume 17: Washington (U.S. Government Printing Office), p. 429-503.
- Bastron, H., Barnett, P.R., and Murata, K.J., 1960. Method for the quantitative spectrochemical analysis of rocks, minerals, ores, and other materials by a powder D-C arc technique: U.S. Geol. Surv. Bull. 1084-G, p. 165-182.
- Cann, J.R., 1970. New model for the structure of the ocean crust: Nature, v. 226, p. 928.

- Clague, D.A., 1974. The Hawaiian-Emperor seamount chain: its petrology, origin, and implications for plate tectonics: Unpublished Ph.D. dissertation, University of California, San Diego.
- Deer, W.A., Howie, R.A., and Zussman, J., 1966. Rockforming minerals, v. 3 and 4; New York (J. Wiley and Sons).
- Engel, A.E.J., Engel, C.G., and Havens, R.G., 1965. Chemical characteristics of oceanic basalts and the upper mantle: Geol. Soc. Am. Bull., v. 76, p. 719-734.
- England, R.N. and Davies, H.L., 1973. Mineralogy of ultramafic cumulates and tectonites from Eastern Papua: Earth Planet. Sci. Lett., v. 17, p. 416-425.
- Evans, B.W. and Wright, T.L., 1972. Composition of liquidus chromite from the 1951 (Kilauea Iki) and 1965 (Makaopuhi) eruptions of Kilauea volcano, Hawaii: Am. Mineralogist, v. 57, p. 217-230.
- Gast, P.W., 1968. Trace element fractionation and the origin of tholeiitic and alkaline magma types: Geochim. Cosmochim. Acta, v. 32, p. 1057-1086.
- Green, D.H. and Ringwood, A.E., 1967. The genesis of basalt magmas: Contrib. Mineral. Petrol., v. 15, p. 103-190.
- Hart, S.R., 1971. K, Rb, Cs, Sr, and Ba contents and Sr isotope ratios of ocean floor basalts: Phil. Trans. Roy. Soc. London, ser. A, v. 268, p. 573-587.
- Himmelberg, G.R. and Coleman, R.G., 1968. Chemistry of primary minerals and rocks from the Red Mountain-Del Puerto ultramafic mass, California: U.S. Geol. Surv. Prof. Paper 600-C, p. C18-C26.
- Himmelberg, G.R. and Loney, R.A., 1973. Petrology of the Vulcan Peak Alpine-type peridotite, Southwestern Oregon: Geol. Soc. Am. Bull., v. 84, p. 1585-1600.
- Hubbard, N.J., 1967. Some trace elements in Hawaiian lavas: Unpublished Ph.D. Thesis, University of Hawaii.
- Hawaiian tholeiitic and Hawaiian alkalic basalts: Earth Planet. Sci. Lett., v. 5, p. 346-352.
- Irvine, T.N., 1967. Chromian spinel as a petrogenetic indicator, Part 2. Petrologic applications: Canadian J. Earth Sci., v. 4, p. 71-103.
- Irvine, T.N. and Baragar, W.R.A., 1971. A guide to the chemical classification of common volcanic rocks: Canadian J. Earth Sci., v. 8, p. 523-548.
- Ishikawa, H., 1968. Some aspects of geochemical trends and fields in the ratios of vanaduim, nickel, and cobalt: Geochim. Cosmochim. Acta, v. 32, p. 913-917.
- Jackson, E.D., 1969. Chemical variation in coexisting chromite and olivine in chromitite zones of the Stillwater Complex: Econ. Geol. Monogr. 4, p. 41-71.
- Jackson, E.D., Green, H.W., II, and Moores, E.M., 1975. The Vourinos Ophiolite, Greece: Cyclic units of lineated cumulates overlying harzburgite tectonite: Geol. Soc. Amer., v. 86, p. 390-395.

- Kay, R., Hubbard, N.J., and Gast, P.W., 1970. Chemical characteristics and origin of oceanic ridge volcanic rocks: J. Geophys. Res., v. 75, p. 1585-1613.
- Kretz, R., 1961. Some application of thermodynamics to coexisting minerals of variable composition—Examples, orthopyroxene-clinopyroxene and orthopyroxene-garnet: J. Geol., v. 69, p. 361-387.
- _____, 1964. Analysis of equilibrium in garnet-biotitesillimanite gneisses from Quebec: J. Petrol., v. 5, 1-20.
- Larson, R.L. and Chase, T.E., 1972. Late Mesozoic evolution of the western Pacific ocean: Geol. Soc. Am. Bull., v. 83, p. 3627-3644.
- Loney, R.A., Himmelberg, G.R., and Coleman, R.G., 1971. Structure and Petrology of the Alpine-type peridotite at Burro Mountain, California, U.S.A.: J. Petrol., v. 12, p. 245-309.
- Macdonald, G.A. and Katsura, T., 1964. Chemical composition of Hawaiian lavas: J. Petrol., v. 5, p. 82-133.
- MacGregor, 1969. The system MgO-SiO₂ and its bearing on the distribution of TiO₂ in basalts: Am. J. Sci., Schairer volume 267-A, p. 342-363.
- Mammerickx, J., Smith, S.M., Taylor, I.L., and Chase, T.E., 1974. Bathymetry of the South Pacific, Chart 13 of 21: Scripps Institution of Oceanography, Institute of Marine Resrouces.
- Melson, W.G. and Thompson, G., 1971. Petrology of a transform fault zone and adjacent ridge segments: Phil. Trans. Roy. Soc. London, ser. A, v. 26, p. 423-441.
- Melson, W.G., Aumento, F., Ade-Hall, J.M., Bougault, M., Dmitriev, L., Fischer, J.F., Flower, M., Howe, R.C., Hyndman, R.D., Miles, G.A., Robinson, P.T., and Wright, T.L., 1975. Deep Sea Drilling Project Leg 37— the volcanic layer: Geotimes, v. 19, p. 16-18.
- Morgan, J.W., 1972. Plate motions and deep mantle convection: Geol. Soc. Am. Mem. 132 (Hess Memorial Volume), p. 7-21.
- Pearce, J.A. and Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth Planet. Sci. Lett., v. 19, p. 290-300.
- Stoeser, D.B., in press. Igneous rocks from Leg 30 of the Deep Sea Drilling Project. In Andrews, J.E., Packham, G., et al. Initial Reports of the Deep Sea Drilling Project, Volume 30: Washington (U.S. Government Printing Office).
- Tatsumoto, M., Hedge, C.E., and Engel, A.E.J., 1965. Potassium, strontium, thorium, uranium, and Sr^{87/86} in oceanic tholeiitic basalt: Science, v. 150, p. 1886.
- Wilson, J.T. and Burke, K., 1973. Plate tectonics and plume mechanics (abstract): EOS Am. Geophys. Union Trans., v. 54, p. 470.
- Winterer, E.L., Lonsdale, P.F., Matthews, J.L., and Rosendahl, B.R., 1974. Structure and acoustic stratigraphy of the Manihiki Plateau: Deep Sea Res., v. 21, p. 793-814.
- Wright, T.L., 1971. Chemistry of Kilauea and Mauna Loa in space and time: U.S. Geol. Surv. Prof. Paper 735.

PLATE 1

Figure 1	Sample from dredge ST11-68D. Pale brown al- tered basalt (B) enclosed in thick manganese crust (M). Green montmorillonite group clays (C) occur as clasts within the manganese. Phosphorite (P) ce- ment is also present. Sample is 8 cm in the longest dimension.
Figure 2	Sample from dredge ST11-68D. Pale brown highly altered basalt surrounded by bright green mont- morillonite group clay alteration. Sample is 3.2 cm in the longest dimension.
Figure 3	Sample ST11-78D-16. Fresh black basalt enclosed in montmorillonite group clay alteration rind. The sample is 2.9 cm across.
Figure 4	Sample ST11-78D-15. Fresh black basalt sur- rounded by symmetrical rind of montmorillonite group clays. Sample is 2.6 cm in diameter.
Figure 5	Photomicrograph showing embayed olivine phenocrysts (xenocrysts?) in Sample ST11-78-15. Width of photograph = 3.4 mm.
Figure 6	Photomicrograph showing both embayed and euhedral olivine phenocrysts (and xenocrysts?) in Sample ST11-78-15. Width of photograph = 3.4 mm.
Figure 7	Photomicrograph showing plumose texture of quench pigeonite in Sample ST11-78-15. Width of photograph $= 0.14$ mm.
Figure 8	Photomicrograph showing quench oliving in Sample ST11-78-14. Note the extreme elongation of the crystals. Width of photograph = 0.9 mm.

















PLATE 2

Figure 1	Photomicrograph showing quench olivine in Sample ST11-78-14. Note the extreme elongation and irregularity of the crystals. Width of photograph $= 0.14$ mm.
Figure 2	Sample ST11-78-23. Gabbroic cumulate showing cumulus olivine crystals altered to serpentine. Euhedral cubes are chromite. Width of photograph $= 0.9$ mm.
Figure 3	Sample ST11-78-23. Gabbroic cumulate showing cumulus olivine crystals altered to fibrous saponite. Euhedral cubes are chrmoite. Width of photograph = 3.4 mm.
Figure 4	Sample ST11-78-23. Gabbroic cumulate showing cumulus olivine crystals altered to fibrous saponite. Euhedral cubes are chromite. Colorless mineral is a Ca-rich zeolite, probably thomsonite or gismondine. The high relief fragments are clinopyroxene. Width of photograph = 0.9 mm.



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