Stable Isotope Geochemistry: A Tribute to Samuel Epstein
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Oxygen and hydrogen isotope compositions of oceanic plutonic rocks: High-temperature deformation and metamorphism of oceanic layer 3

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Abstract—Oxygen and hydrogen isotopic data from three suites of modern oceanic plutonic rocks are presented: (a) dredged gabbro, diorite, and aplite from the southern Mid-Atlantic Ridge; (b) dredged gabbro, plagiogranite, diorite, ferrogabbro, and a quartz monzonite from five fracture zones in the western Indian Ocean; and (c) a 500-meter core of olivine gabbro, norite, troctolite, ferrogabbro, and trondjemite drilled from the intersection of the Atlantis II fracture zone and the Southwest Indian Ridge. Essentially all samples bear isotopic and mineralogic evidence of high to moderate temperature hydrothermal metamorphism by seawater. Maximum temperatures of alteration are above 600°C; lower temperatures of alteration, greenschist and below, are not characteristic. Whole-rock samples and plagioclase separates have undergone ^{18}O depletions associated with deformation and development of metamorphic mineral assemblages. The stratigraphic control provided by the drill core allows detailed correlation between depth and $^{18}O/^{16}O$ effects, as well as the correlation with pervasive deformation textures and major faults that provided the permeability for seawater to penetrate deeply into oceanic layer 3. The abundance of hydrous alteration minerals can be correlated with the water-rock ratio. Igneous pyroxene has not undergone appreciable isotopic exchange with seawater except under conditions of dynamic recrystallization. Rather, it is either relict or is replaced by amphibole in isotopic equilibrium with plagioclase. Silicic igneous rocks have apparently undergone isotopic exchange in the same range of temperatures as metagabbros. There is some evidence of local assimilation of hydrothermally altered metagabbro by late-stage magma. Isotopic evidence is provided for the presence of a hydrous fluid enriched in ^{18}O by up to 4.5 per mil and depleted in D by 30 per mil compared to seawater. This fluid is either an evolved seawater-hydrothermal fluid, perhaps derived from a late hydrous magma, or a hybrid resulting from mixing between magmatic water and seawater during the waning stages of magmatic activity.

INTRODUCTION

PLUTONIC ROCKS ARE a major constituent of the oceanic crust and presumably comprise most of oceanic layer 3. Detailed petrologic and isotopic studies of oceanic gabbros have suggested that metamorphic recrystallization is related to deformation and/or interaction with seawater during the progressive cooling of the gabbroic sequence (STAKES *et al.*, 1991; MEVEL, 1988; STAKES and VANKO, 1986; BATIZA and VANKO, 1985; ITO and ANDERSON, 1983; BONATTI *et al.*, 1975). The controls on the initial penetration of seawater into the lower crust, the extent and temperatures of seawater circulation, and the possible interaction between high-temperature metamorphism and late-stage magmatic processes can be inferred from the stable isotopic compositions of modern oceanic plutonic rocks.

This study presents a wealth of new oxygen and hydrogen isotopic data from three suites of oceanic plutonic rocks. Drilled and dredged gabbroic and silicic rocks from the western Indian Ocean comprise one of the largest suites of plutonic rocks. These are complemented by a suite of evolved rocks—diorites, aplites, and plagiogranites—from the southern Mid-Atlantic Ridge. This study will investigate whether seawater penetrates and extensively alters these sections of lower oceanic crust at high temperatures, and whether high-temperature shear zones play an important role in the metamorphism of the lower crust.

SAMPLE SUITES ANALYZED FOR THIS STUDY

Petrography and mineral identification for each suite of rocks are from previous studies (ENGEL and FISHER, 1975; FREY *et al.*, 1991; STAKES *et al.*, 1991; VANKO and STAKES, 1991). Additional microprobe analyses are provided for samples from the Indian Ocean suites. These analyses were performed on the fully automated Cameca SX-50 electron microprobe at the University of South Carolina, using natural minerals for standards. Special efforts were made to determine plagioclase zonation, evidence of secondary or recrystallized pyroxene, and intergrown minerals in hydrothermal coronas. Trace minerals were identified using the Kevex EDS system on the microprobe. All three suites of samples contain evolved silicic rocks comprised of plagioclase, quartz, and other minerals. These silicic rocks are referred to as aplites or plagiogranites unless biotite or phlogopite is identified as an accessory mineral. Silicic rocks containing mica are referred to as trondjemites.

Samples from 22°S on the Mid-Atlantic Ridge

Gabbros, diorites, and an aplite dredged from a fracture zone at 22°S on the Mid-Atlantic Ridge (MAR) were an-

Table 1. Oxygen isotopic composition of dredged rocks.

Sample no.	Rock type	Mineralogy	WR	PLAG	AMPH	PX	QTZ	Other
A. MAR 22°S								
SILICIC ROCKS:								
12-32G	FE-DI	f, ol, cpx, ap, hb, mt, ilm	7.1	6.3	4.6		7.4	
12-32W	PLGT DK	q, ab	7.0	5.9			7.0	
12-22	FE-DI	f, ol, cpx, hb, mt, ilm, ap	6.6	6.5				
12-11C	FE-DI	f, ol, cpx, ap, ilm, hb, mt	3.7	4.2	2.5			
12-11FG	FE-DI	f, ol, px, ap, hb, mt, ilm	4.4	4.9	3.3			
12-24	Q-DI	f, q, cpx, hb, ilm, ap, xn	5.1	4.6	4.6		6.4	
12-3D	GB	f, hb	6.3	6.2	3.8			
12-16	FE-DI	f, hb, cpx	6.2	6.4	5.1		6.7	
12-36	FE-DI	f, hb	6.4	5.3			7.4	
GABBROS:								
5-38	OL-GB	f, ol, cpx, ilm	5.7	5.6		5.7		5.3OL
5-9	OL-GB	f, ol, cpx, mt, ilm, chl	5.7	5.9		5.5		
5-62	OL-GB	f, ol, cpx, mt, ilm	5.9	6.0		5.6		
B. INDIAN OCEAN								
SILICIC ROCKS:								
ANTP125-4B	GR DB	f, hb, kf, q, ap	5.4	6.4	4.4			
ANTP125-4C	Q-MZ DK	f, hb, q, kf, bt, ap, sp	7.5	7.3	4.7		8.7	
ANTP125-10	DI	f, hb	2.8	4.5	2.5			
ANTP125-13	PLGT	f, hb, q, chl	5.0	6.4	4.6			
ANTP125-14	S-DI	f, hb, tc, bt	5.3	5.7	1.4			
ANTP125-16	PLGT	f, hb, q, ap, sp	4.4	3.9			5.7	
GABBROS:								
ANTP125-2(2)	PX GB	f, cpx, opx, hb	5.2	5.9	5.4	5.3		
ANTP125-8	FETI GB	f, cpx, opx, tc, chl	5.7	6.5		5.7		
ANTP126-1(4)	OL GB	f, ol, cpx, hb, opx, tc, chl	4.9	5.4		5.5		
ANTP130-1(2)	OL GB	f, ol, cpx, sm	6.2	6.3		5.7		
ANTP130-4	GB	f, ol, cpx, act, tc, chl, z	7.8	7.0	5.6	5.6		13.4 Z
ANTP130-6	OL GB	f, ol, tc	6.0	6.6		5.5		
CIR82-1	PX GB	f, cpx, opx, hb, chl	5.0	5.2	3.7	5.3		
CIR97B	OL GB	f, ol, cpx, hb, opx, chl, tc	4.7	5.3		5.2		
CIR97D	OL GB	f, ol, cpx, tc, chl, sm	5.0	5.0		5.2		
AMPHIBOLITIZED GABBROS:								
ANTP113-1(1)	PX GB	f, cpx, hb,	3.8	4.5	4.6			
ANTP125-1	HB GB	f, cpx, hb, opx, ap	2.3	3.1	1.5	5.0		
ANTP130-1(1)	OL GB	f, ol, cpx, tc, mt	4.9	4.1	4.1	5.1		
ANTP130-3	HB GB	f, hb, cpx	5.3	4.9	4.7	5.2		
ANTP130-8	PX GB	f, cpx, hb, opx, tc, chl, z		5.3		5.4		
CIR97ZZ	PX GB	f, hb, cpx	3.7	3.5	3.4			
CIR97C	HB GB	f, hb	4.9		4.7			
CIR97F(2)	HB GB	f, hb, ilm	4.1	4.5	4.1			
CIR97X	S-GB	f, hb, ab	4.7	4.6	4.9			

Notes: f = feldspar; ol = olivine; cpx = clinopyroxene; hb = hornblende; opx = orthopyroxene; act = actinolite; tc = talc; chl = chlorite; sm = smectite; ap = apatite; z = zeolite; ilm = ilmenite; mt = magnetite; ab = albite; bt = biotite; q = quartz; sp = titanite; kf = K-feldspar; GB = gabbro; PX = pyroxene; S-GB = deformed gabbro; FETI = ferrogabbro; PLGT = plagiogranite; DI = diorite; Q-MZ DK = quartz monzonite dike; GR DB = granophyric diabase.

alyzed for oxygen isotopes. Complete petrographic and geochemical descriptions of these samples are provided in FREY *et al.* (1991) and a summary is provided here. The isotopic results for both whole rock and mineral separates are provided in Table 1. All the gabbros and diorites from 22°S have cumulate textures. Samples 5-9, 5-38, and 5-62 are petrographically the freshest olivine gabbros obtained, and contain cumulate plagioclase, olivine, and pyroxene. Ilmenite, magnetite, and sulfides are accessory minerals. Trace amounts of chlorite were observed in microfractures cutting plagioclase in sample 5-9. The plagioclase compositions in 5-9, and 5-38 are very uniform at An62 and An69, respectively. The plagioclase in sample 5-62 is variable in grain size and strongly zoned with cores of An56.

Samples 12-22, 12-11C, 12-11FG, 12-30, and 12-32G are characterized as ferrodiorites by FREY *et al.* (1991), although they have lower SiO_2 than typical diorites. These samples contain sodic plagioclase (An30-An8), olivine partially to completely altered to amphibole and magnetite, pyroxene partially altered to amphibole, primary brown hornblende partially altered to green amphibole, magnetite, ilmenite, and apatite. Relict olivine is preserved only in sample 12-32 and is very Fe-rich (Fo14), similar to the ferrogabbros of ODP Hole 735B (discussed below). Samples of quartz-diorite (12-16, 12-24, 12-36) are composed of quartz, sodic plagioclase (An10), pyroxene partially altered to amphibole, primary green amphibole with minor apatite, ilmenite, and xenotime. An aplite dike (12-32W) that cross-cuts ferrodiorite sample 12-32G is composed of quartz and albite (An2) in a sugary, equigranular texture with grain-size that decreases toward the center of the vein. The amphiboles may in part be xenocrysts from the host diorite.

Samples from Indian Ocean fracture zones

A suite of 24 gabbroic rocks dredged from five fracture zones in the western Indian Ocean were analyzed for oxygen and hydrogen isotopes. Geographic distribution and detailed mineral chemistry of the complete set of dredge hauls is described in ENGEL and FISHER (1975) and BLOOMER *et al.* (1989). Rocks from the Vema (ANTP130), Argo (ANTP125, ANTP126, CIR82), Marie Celeste (CIR97), and Melville (ANTP113) fracture zones were selected for study. Detailed studies of primary mineral compositions in gabbroic rocks led BLOOMER *et al.* (1989) to suggest that these represent cumulates in small sills or chambers emplaced laterally from a central axial magma chamber. Boundary layer crystallization and partial resorption of wall rock are suggested to play a role in the extensive mineral variability observed in these samples.

Most of the samples included in this isotopic study are described by ENGEL and FISHER (1975), with a comparison to ophiolitic samples presented in STAKES *et al.* (1984). Detailed mineralogy and isotopic results are presented in Table 1. The samples include olivine gabbros (ANTP130B-1(2A), -4, -6; ANTP126-1(4); CIR97B, -D), two pyroxene gabbros (ANTP125-2(2); CIR82-1), and a Ti-ferrogabbro (ANTP125-8), all of which contain minor to trace amounts of secondary hydrous minerals. The mineralogy of these hydrous minerals is controlled by the primary mineral being replaced during static hydrous or coronitic alteration (STAKES *et al.*, 1984).

Amphibolitized gabbros are extensively replaced by metamorphic minerals, dominantly hornblende or actinolite. Sample ANTP125-1 contains metamorphic pyroxene and brown hornblende that may have formed during high-temperature deformation, now obscured by extensive hydrous alteration. Plagioclase is variable in composition (An46-An29) with rims containing up to 3% Or and small needles of apatite. Augite gabbros (ANTP113-1(1); CIR97ZZ) similarly contain intermediate plagioclase (An53-An48) and amphibole ranging from actinolite to edenitic or magnesio-hornblende in composition. Sample CIR97ZZ, in addition, shows evidence of a deformed plagioclase mosaic (An40) cross-cut by a vein of ferroan pargasitic hornblende. Olivine-bearing rocks (*e.g.* 130B-1(1), Fo68) and orthopyroxene-bearing rocks (*e.g.* 130B-8) contain talc-magnetite pseudomorphs in addition to plagioclase (An64-An52) with local sodic rims and hornblende replacing both the plagioclase and most clinopyroxene. Pyroxene symplectites and small plagioclase grains may be artifacts of an early episode of ductile deformation.

The hornblende-rich gabbros (ANTP130-3; CIR97C; -F(2)) and the cataclastic anorthosite (CIR97X) are predominantly composed of plagioclase of intermediate composition (An58-An45) and aluminous hornblende, with zones of ductile deformation similar to those in the amphibolitized gabbros. These samples also exhibit a later cataclastic deformation characterized by the formation of more sodic plagioclase (An39-An8) in overgrowths, granulated zones, or network veins.

Silicic rocks from the Indian Ocean dredge suites were all collected from the Argo Fracture Zone (ANTP125) and include a diorite (10) and a mylonitized diorite (14), aplite or trondjemite (13, 16), and a granophyric diabase host (4B) for a dikelet of quartz monzonite (4C). The latter two samples are unusual in containing rims of orthoclase. The quartz monzonite dikelet, in addition, contains zircon and biotite, and is described in detail in ENGEL and FISHER (1975). The primary minerals include sodic plagioclase (An18-An36), ferro-edenitic hornblende, and variable amounts of quartz.

Samples from ODP Leg 118, Hole 735B

Cored gabbros, ferrogabbros, and trondjemites recovered from ODP Hole 735B in 1987 represent 500 m of oceanic layer 3 that formed at the Southwest Indian Ridge 18 km from its intersection with the Atlantis II Fracture Zone. The lithostratigraphy and igneous mineralogy of these samples are described in detail in DICK *et al.* (1991) and NATLAND *et al.* (1991). The primary lithostratigraphy is illustrated in Fig. 1, with core numbers and depth in the core. Most of the core (61%) is chemically uniform, massive olivine gabbro with minor cryptic variations. Plagioclase is moderately anorthitic (An58) while the olivine and clinopyroxene are both magnesian (Mg# = 81, Fo74, respectively). A small unit of gabbronorite caps the section while the lower 80 m contains intercalated troctolite and microgabbro. The grain size is highly variable, and contacts between the six lithologic units are frequently sheared and deformed.

The remainder of the core is comprised of abundant Ti-ferrogabbro rich in ilmenite and magnetite, together with small volumes of late felsic veins and intrusives. The oxide-rich gabbros are interpreted to be derived by extensive high-iron differentiation of the olivine gabbros, followed by mechanical concentration of the Fe-rich fractionate into permeable shear zones by filter pressing and deformation. This is associated with the latter stages of cooling and crystallization at a spreading axis (NATLAND *et al.*, 1991; DICK *et al.*, 1991). DICK *et al.* (1991) refer to these oxide-rich gabbros as products of "syndeformational magmatic fractionation."

Late felsic intrusives include trondjemite and aplite that are mineralogically and stratigraphically associated with diopside-plagioclase veins. The felsic veins and intrusives typically contain biotite, phlogopite, and zircon. Both the felsic intrusives and the diopside-bearing veins have characteristically suffered from low-temperature alteration (greenschist to zeolite grade), obscuring primary mineral relationships (STAKES *et al.*, 1991). DICK *et al.* (1991) suggest that the felsic intrusions are the silicic complement to the ferrogabbros, forming by magmatic hydrofracture in brecciated zones that dominate the lower half of the core, presumably as a result of localization of the late hydrous magmas. NATLAND *et al.* (1991) suggest that liquid immiscibility played a role in the formation of the silicic differentiates. STAKES *et al.* (1991) describe textural features more consistent with assimilation or partial resorption of hydrothermally altered gabbroic wall rock. The largest trondjemite horizon is found between cores 53R and 56R and contains partially resorbed xenoliths of gabbro, distinguished by euhedral sodic plagioclase mantling partially digested calcic plagioclase.

The metamorphic history and stratigraphy of the drillcore is described in detail by STAKES *et al.* (1991) and VANKO and STAKES (1991). The core is dissected by ductile deformation zones that are apparently related to normal faulting (CANNAT *et al.,* 1991a,b). The textural log from STAKES *et al.* (1991) is provided in Fig. 1, as a compilation of ductile deformation from faintly foliated (Type I) to mylonitic (Type V). Metamorphic mineral assemblages suggest that ductile deformation was initiated under granulite to amphibolite grade conditions and terminated in lower amphibolite conditions. A crack and vein network that dominates the upper half of the core resulted from brittle failure at the conclusion of the ductile deformation. A histogram provided in Fig. 1 illustrates the relationship between extensional veins oriented perpendicular to the metamorphic foliation and intensity of deformation. The veins related to deformation are either hornblende-bearing or hornblende- and sodic plagioclase-bearing, and are the most abundant vein type in the upper 250 m of core. Similar amphibole veins are also present sporadically in the lower 50 m of core. Hydrous or coronitic alteration of the gabbro to assemblages including cummingtonite, talc, hornblende of variable composition, sodic plagioclase, Mg-rich chlorite, clinozoisite, and phlogopite is correlated with penetration by brittle cracks and veins.

The felsic intrusions and diopside-bearing leucocratic veins are abundant in the lower half of the core, spacially associated with brecciated horizons (see Fig. 1). The largest leucocratic veins are found in the undeformed horizon between cores 60 and 75. Within this horizon diopside not only appears in monomineralic veins but also as a replacement of igneous pyroxene and plagioclase. Most of the veins in the lower 250 m of core represented in the histogram of Fig. 1 are diopside-plagioclase or their altered equivalent. The brecciated horizons are the only portion of the core that exhibit mineral assemblages characteristic of greenschist- and zeolite-grade metamorphism, including epidote, sphene, chlorite, actinolite, thomsonite, and analcime. Continued alteration by cold seawater within some of the brecciated horizons is demonstrated by the presence of late, low-temperature carbonate-smectite veins (see Fig. 1).

RESULTS OF ISOTOPIC ANALYSES

Oxygen and hydrogen isotopic analyses were performed on whole rocks and mineral separates. Results are reported in standard δ-notation relative to SMOW; NBS-28 has a $\delta^{18}O = +9.6$ on this scale. Minerals were mechanically separated and then hand-picked and cleaned with acetone prior to isotopic analyses. Traces of carbonate were removed by reaction with cold dilute hydrochloric acid. In addition, quartz separates were cleaned with cold hydrofluoric acid to insure purity. When possible, multiple generations of feldspar and amphibole were separated from single samples, based on grain size and optical properties.

Results of isotopic analyses from the dredged rocks are provided in Table 1. These analyses were performed at the California Institute of Technology using fluorine gas as a reagent. Samples from Hole 735B (Table 2) are distinguished as veins versus matrix, and these subsamples separated where possible. Other samples are from homogeneous bulk rock, some of which include veinlets too small to separate. Mineral separates from Hole 735B include plagioclase, clinopyroxene, metamorphic diopside, hornblende, olivine, epidote, and biotite. Homogenous whole-rock powders were produced during the cruise for the purpose of shipboard chemical analyses. Isotopic analyses performed on these powders were reported in STAKES *et al.* (1991) and are provided in Fig. 1. All of these analyses were performed at the University of South Carolina using ClF_3 as a reagent. Hydrogen isotopic analyses (Table

FIG. 1. Metamorphic and deformation stratigraphy for ODP Hole 735B (after STAKES *et al.,* 1991). From left to right the columns represent: (1) Depth (in meters below seafloor) and core number (1 to 87) using lithostratigraphic designations from DICK *et al.* (1991): Unit I = gabbro norite; Unit II = compound olivine and oxide gabbro; Unit III = disseminated oxide-olivine gabbro; Unit IV = massive oxide olivine gabbro; Unit V = massive olivine gabbro; Unit VI = compound olivine, oxide, and troctolitic gabbro. (2) Textural type as an indicator of extent of synkinematic recrystallization showing structural domains and major mylonite zones (M): I = weakly deformed with no penetrative deformation; II = well-foliated with limited plagioclase recrystallization; III = well-foliated with extensive plagioclase recrystallization and gneissic layering; IV = intercalated gneissic and mylonitic layering; V = mylonitic. (3) Histogram of number of veins per core, with patterned intervals representing heavily veined brecciated horizons; the veins are dominantly hornblende-bearing to bottom of Core 54, diopside-bearing below Core 54, and carbonate veins are indicated by arrows. (4) Profile of $\delta^{18}O$ vs. depth, with symbols as follows: filled circles = whole-rock powders; × = vein hornblende; filled square = vein plagioclase; open square = matrix plagioclase; open triangle pointing up = whole-rock plagioclase; open triangle pointing down = whole-rock hornblende.

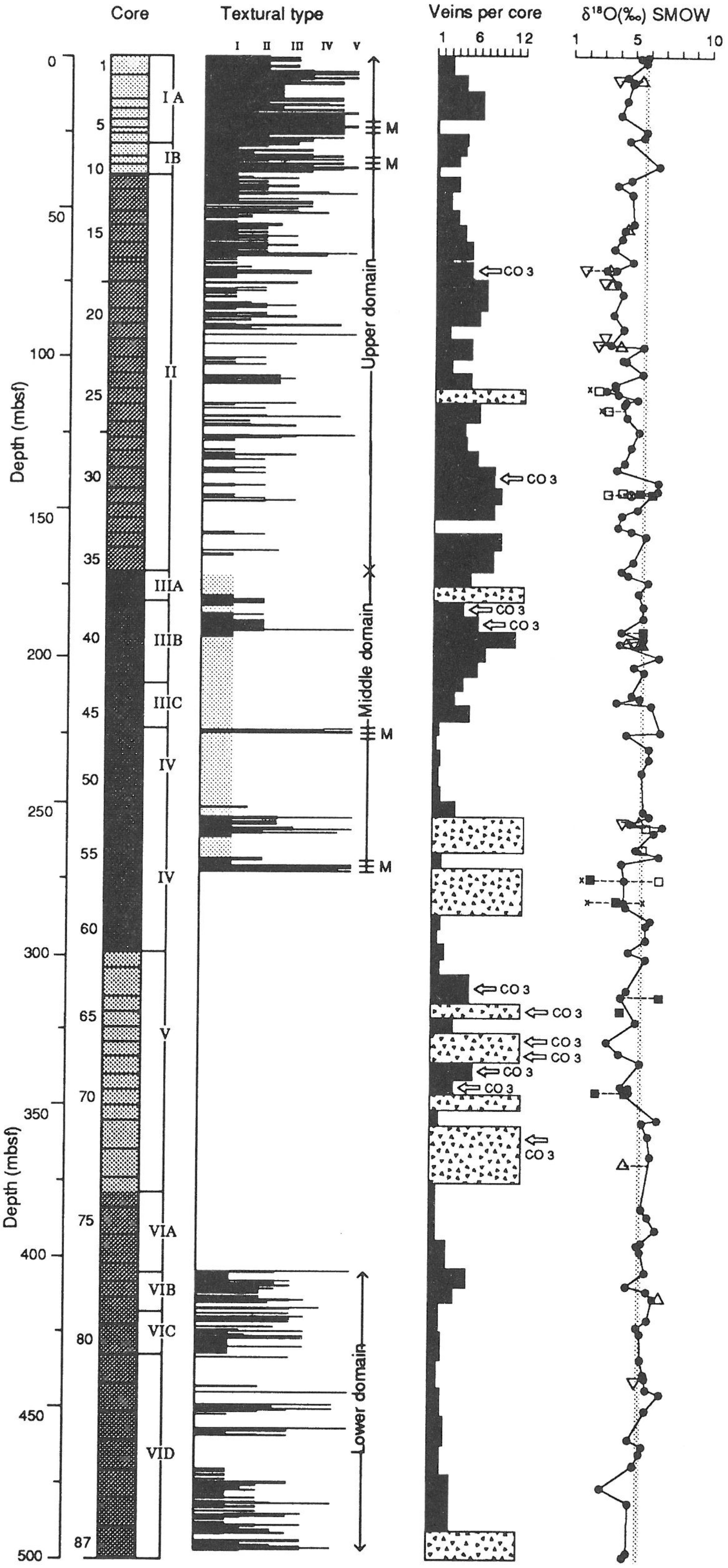
Core
Textural type
I II III IV V
Veins per core
1 6 12
δ18O(‰) SMOW
1 5 10
Depth (mbsf)
0
50
100
150
200
250
300
350
400
450
500
1 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 87
IA
IB
II
IIIA
IIIB
IIIC
IV
V
VIA
VIB
VIC
VID
Upper domain
Middle domain
Lower domain
M
CO 3

Table 2. Oxygen isotope data for ODP Hole 735B.

CORE-SEC	Interval	Depth	WR	PLAG	AMPH	DI	CPX	Other
2-2	36-39	8.4	VEIN	4.8	4.2			
4-2	37-43	19.4		6.5				
10-1	37-39	36.6		6.6	6.1		5.8	
12-1	114-117	40.5		4.6	4.5		4.1(A)	
12-2	135-139	42.2	3.6	4.7				
15-1	90-93	57.1	4.2	4.4				
16-1	151-154	63.3		4.9	1.9			
18-3	5-8	71.6	3.2	3.2	1.6			
19-1	124-128	75.9	3.8	3.4	2.9			
19-3	5-9	77.7						
22-1	56-62				3.2			
22-1	69-73	94.7			3.3			
22-1	142-147	95.5	3.3	3.9	3.0			
22-3	112-115	98.2	VEIN	4.0	3.6			
24-1	128-131	107.4		5.3	2.1		3.4(A)	
24-2	47-51	108.1	3.6					
25-1	12-17	110.6	Ca-plg	4.9				
			Na-plg	2.4	1.9			
26-2	8-12	117.1		3.3	2.7		5.1	
31-2	100-104	146.1	4.1					
			VEIN	5.3				
31-3	31-33	146.7	3.6	3.5	5.3			
			VEIN	5.7				
33-1	137-141	154.8		4.4	4.0	2.5		
36-1	117-119	173.0	VEIN	5.8				
35-6	114-117	171.9	4.3				5.4	
38-4	140-143			5.7			5.8	
40-2	73-78	192.2	4.2					
			VEIN	6.1				
40-3	34-39	193.3	VEIN			1.9		
41-1	42-50	196.9	4.2	4.5	4.8		5.2	
41-3	67-71	200.1	VEIN	6.9(A)				
44-4	41-49	215.5	3.9					
53-4	5-15	256.9	4.7	5.3	4.4			
55-1	59-69	265.3	5.3	3.2	4.2			
56-1	54-61	270.7	4.3					
57-2	11-18	276.4	4.4	4.0	5.3		5.5	
57-4	0-6	277.9	VEIN	6.6				
58-3	8-16	283.3	4.4					
			VEIN	3.9	2.1		5.6	
60-4	105-112	295.5	VEIN	7.34(A)	4.0	1.7		
					2.6ACT			
61-3	48-58	299.0	4.7					
63-1	107-113	309.4	VEIN	4.3	4.9HB	1.7		
					2.5ACT			
63-5	70-77	311.1	VEIN	5.6	5.4			
			MATRIX	4.9				
63-6	94-98	313.4	VEIN	6.8		4.0		
			MATRIX	6.3				
63-7	80-87	314.6	4.2					
			VEIN C	4.1		2.4		
			VEIN F (A)	7.0				
64-3	95-104	319.3	VEIN	4.1				
66-4	14-19	329.4	3.4					
68-2	68-75	337.2		7.4		1.1		
69-1	41-48	341.5	VEIN	4.8			5.2	
69-3	86-96	334.5	4.9	7.2				
70-1	39-49	346.4	VEIN	4.7		2.7		
70-1	130-140	347.3	5.7	5.3		5.2		4.8OL
70-2	11-13		VEIN C	5.0		2.9		
			VEIN F	6.6				
72-7	42-47	360.1		4.7				
73-6	60-65	372.9		7.5	5.4			

Table 2. (Continued)

CORE-SEC	Interval	Depth	WR	PLAG	AMPH	DI	CPX	Other
74-5	104-109	382.3		6.5			5.1	
75-1	0-6	385.2	6.0					
76-2	121-126	396.5	5.5		4.9		4.3	
77-5	15-19	409.1	4.7					
78-3	110-119	413.4	6.6					
			VEIN	6.8				
79-4	46-49	419.5	VEIN	6.0		2.6		
79-6	69-77	422.5	6.4	7.2			5.7	4.9OL
80-7	27-34	433.1	5.8					
81-2	23-31	436.1	VEIN	7.9	6.0			
81-4	60-68	438.4	6.3		6.0			
81-6	87-90	441.3		6.3	5.3			
		NAPL	VEIN	5.8	5.7			
82-2	58-65	445.1	7.2		5.7			
82-7	21-29	451.8	6.2	6.2			5.6	
83-5	36-46	460.1	5.1					5.4BT
84-2	70-78	464.2	5.7					
84-6	0-8	468.7	VEIN	6.5		1.8		3.8EP
85-4	17-25	476.0	3.0					
85-6	11-15	478.6		5.0		1.4		3.5EP
86-6	15-18	489.4		7.5		1.0		
86-6	91-96	490.1		7.7	5.3		5.3	
87-5	79-86	497.4	4.9	4.7	3.8	5.7		
			VEIN		3.4			
87-7	7-14		MATRIX	3.0				
			VEIN C	4.5		1.4		
			VEIN F	6.2				

Notes: VEIN C = coarse-grained vein mineral; VEIN F = fine grained vein mineral; Minerals: PLAG = plagioclase; AMPH = amphibole; CPX = clinopyroxene (igneous or dynamic recrystallization); DI = secondary diopside; OL = olivine; EP = epidote; BT = biotite; ACT = actinolite; HB = dark green to brown hornblende.

3) were performed on hornblende separates from Indian Ocean dredged samples and the Hole 735B gabbros. These analyses were all performed at the U.S. Geological Survey in Menlo Park using an RF induction furnace to liberate the water from the mineral and reducing this to hydrogen by reaction with a heated uranium furnace.

The $\delta^{18}O$ of mid-ocean ridge basalt is relatively constant (+5.8; TAYLOR, 1968), and plutonic rocks that have crystallized from such magmas with no seawater involvement would have a whole-rock value similar to this. Isotopic exchange among the crystallizing phases, however, can continue with plagioclase (and quartz) becoming enriched, and pyroxene or hornblende becoming depleted in ^{18}O with decreasing temperatures. The result of closed-system crystal fractionation of olivine would produce evolved magmas (ferrogabbros, diorites, plagiogranites) that are slightly enriched in ^{18}O. Such ^{18}O enrichments with no complication by seawater are typically less than one per mil, and have only been documented in a limited number of suites of oceanic island basalts and their differentiates (see TAYLOR, 1986, for a summary). The mineralogical and isotopic effects of sub-seafloor metamorphism on oceanic layer 3 has been described for ophiolitic rocks and for suites of oceanic gabbros (see MUEHLENBACHS, 1986, for a review). At temperatures above about 250°C, the plutonic rocks are depleted in ^{18}O, with plagioclase exchanging at a rate approximately five times that of pyroxene (see GREGORY *et al.*, 1989; GREGORY and CRISS, 1986). An additional complicating factor is that the effect of seawater interaction is not merely an isotopic exchange: at temperatures below granulite grade, calcic plagioclase is replaced by more sodic compositions and pyroxene is replaced by amphibole. These metamorphic alteration minerals would presumably be in isotopic equilibrium with the local fluid phase, either seawater or an ^{18}O-enriched derivative.

MAR plutonic rocks

The ^{18}O values of the whole-rock powders from the MAR 22°S plutonic rocks vary from +3.7 to +7.0, covering a range anticipated for both fresh and hydrothermally altered rocks. Silicic rocks include the isotopically heavier values, consistent with

Table 3. Hydrogen and oxygen isotopic compositions of hornblendes (per mil relative to SMOW).

Sample	$\delta^{18}O$	δD	
DREDGED GABBROS:			
ANTP125-1	1.5	−43	
ANTP113-1(1)	4.6	−43	
ANTP125-4B	4.4	−57	Host for qtz-monzonite dikelet
ANTP125-2(2)	5.4	−38	
ANTP130-3	4.7	−46	
CIR97C	4.6	−41	
CIR97X	4.7	−46	
CIR97F(2)	4.1	−45	
CIR97ZZ	3.4	−37	
ODP DRILLCORE GABBROS:			
22-1, 69-73	3.2	−49	
55-1, 59-69	4.2	−66	Trondjemite with xenoliths
57-2, 11-18	5.3	−59	Trondjemite with xenoliths
70-1, 130-134	5.2	−43	
76-2, 121-126	4.9	−44	
81-4, 60-68	6.0	−54	
81-6, 87-90	5.3	−50	Vein
87-5, 79-86	3.4	−63	Vein with diopside

the slight ^{18}O enrichments predicted for closed-system fractionation. The quartz separates from the silicic rocks have $\delta^{18}O$ values that are normal to depleted compared to continental granitic rocks (+7.4 to +6.4). Plagioclase separates from these rocks vary from +4.2 to +6.5, comprising fresh and depleted values. In contrast, pyroxene separates are very limited in range, +5.5 to +5.7, consistent with primary igneous values. Values for amphibole, +4.6 to +2.5, are all slightly depleted in ^{18}O compared to what would be expected for primary igneous phases.

Indian Ocean dredged rocks

Within the suite of plutonic rocks dredged from the Indian Ocean fracture zones two groups of gabbros are considered separately: *gabbros* with limited coronitic alteration, and *amphibolitized gabbros* that are extensively replaced by secondary plagioclase and hornblende. The gabbros have whole-rock isotopic compositions that are either normal or depleted in ^{18}O compared to pristine gabbros. The single exception is ANTP130-4, where both the whole-rock and the plagioclase are enriched in ^{18}O, likely associated with replacement of the plagioclase by an ^{18}O-enriched zeolite ($\delta^{18}O$ = +13.4). The other plagioclase separates in the gabbroic rocks vary from slightly ^{18}O-depleted values ($\delta^{18}O$ = +5.0) to slightly enriched values ($\delta^{18}O$ = +6.6). Similar to the MAR suite, the pyroxene isotopic compositions are less variable than those observed for plagioclase, ranging from $\delta^{18}O$ = +5.2 to +5.7. Amphiboles in the gabbros are either identical to the pyroxenes (two samples) or strongly depleted in ^{18}O (one sample).

Within the group of amphibolitized gabbros, all whole-rock samples, all plagioclase separates, and all amphibole separates are strongly depleted in ^{18}O. Pyroxene separates are isotopically uniform, but slightly depleted in ^{18}O compared to the gabbro average composition. The silicic rocks from this suite are extremely heterogeneous in isotopic composition. The quartz-monzonite dikelet, its granophyric diabase host, and one of the plagiogranite samples all contain ^{18}O-rich plagioclase. In contrast, the diorite and the second plagiogranite are extremely depleted in ^{18}O. Quartz from the ^{18}O-depleted plagiogranite is three per mil heavier than that separated from the monzonite dikelet, even though the quartz-plagiclase fractionations are similar (Δ = 1.8 and 1.4, respectively). The amphibole $^{18}O/^{16}O$ ratios are within the same range as observed in the MAR suite.

ODP Leg 118 Site 735B samples

The whole-rock $\delta^{18}O$ variations in the drillcore are illustrated in Fig. 1. In the upper half of the core the gabbros are uniformly and pervasively depleted in ^{18}O, except in limited undeformed regions (STAKES *et al.*, 1991). In the lower half of the core, most zones are slightly enriched in ^{18}O or undepleted, except in brecciated portions of the core. Plagioclase separated from the upper half of the core (down to sample 735B-118-58) has a normal igneous value or is depleted in ^{18}O. The only exceptions are two veins which contain plagioclase partially altered to zeolites. Felsic veins typically show extensive low-temperature alteration, making their origin (metamorphic versus igneous) ambiguous (VANKO and STAKES, 1991; STAKES *et al.*, 1991). Plagioclases in the lower half of the core are extremely variable, from enriched values of $\delta^{18}O$ = +7.9 to values as low as +3.0.

With only one exception, the amphiboles in the upper half of the core are strongly depleted in ^{18}O. In contrast, in the lower half of the core, the amphiboles commonly have $\delta^{18}O > +5$, mirroring the general ^{18}O enrichment in the associated plagioclase and the bulk rock. In the lower half of the core diopside occurs as a replacement of igneous pyroxene and plagioclase, and is more common as a mafic vein mineral than is hornblende (VANKO and STAKES, 1991). Except for one sample, diopside is lower in $\delta^{18}O$ (+1.5 to +3.0) than the pyroxenes in fresh gabbros. The igneous clinopyroxene, in contrast, commonly retains an igneous isotopic composition, falling below $\delta^{18}O = +5.0$ in only a few samples. The presence of ^{18}O-depleted pyroxene is optically correlated with syn-deformational recrystallization.

Hydrogen isotope compositions of amphibole separates

Most hornblende separates have relatively uniform δD values between −37 and −50 (Table 3). However, one hornblende sample from the dredged suite and several from the drillcore have δD values that are up to 15 per mil lighter than this range. Chemical composition plays a role in determining the δD value, with Fe-rich minerals typically lower in deuterium. The hornblende separates from the drillcore are relatively Fe-rich pargasites, ferroan pargasites, and edenites. However the low-D hornblendes are not consistently richer in iron than the other hornblende samples. The most consistent attribute of the low-D hornblendes is their association with the silicic differentiates. The only low-D sample from the dredged rocks is from the host for the quartz-monzonite dikelet. The lowest-D samples from the drillcore are from trondjemite horizons containing partially digested gabbro xenoliths.

FACTORS THAT CONTROL THE ISOTOPIC COMPOSITION OF OCEANIC PLUTONIC ROCKS

The oxygen isotopic compositions of the oceanic plutonic rocks reflect pervasive seawater metamorphism that has resulted in modest to extensive depletions in ^{18}O. The paucity of isotopically pristine gabbroic rocks, even within the drillcore, suggests that much of oceanic layer 3 has been modified by seawater metamorphism. In the following discussion, the relationship of the ^{18}O depletion to secondary mineralogy and deformation will be examined to address the question of the mechanism of seawater penetration into the crystalline oceanic crust.

Mineralogy and $^{18}O/^{16}O$ composition

STAKES *et al.* (1991) show a rough correlation between the quantity of primary pyroxene replaced by amphibole (used as an alteration index) and the ^{18}O-depletion of the ODP Leg 118 gabbros. The static hydrous replacement of pyroxene is only one of a series of predictable mineralogical replacements that is characteristic of these suites of rocks. Both undeformed and dynamically recrystallized pyroxenes are replaced by amphibole. Olivine is replaced by talc and tremolite or cummingtonite (low percentage of replacement), and olivine and plagioclase margins are replaced by chloritic or micaceous coronas (high percentage of replacement). These replacement assemblages are typically depleted in ^{18}O compared to the original mineral phase. Coexisting plagioclase is similarly depleted in ^{18}O, and presumably is also partially replaced by secondary plagioclase (although this is not optically conspicuous).

For both the Indian Ocean dredged rocks (Table 1) and the Hole 735B drillcore (Table 2), the presence of chlorite and talc is commonly (though not perfectly) correlated with low $\delta^{18}O$ values in gabbroic rocks that are mineralogically only slightly altered. The presence of zeolites or analcime, in contrast, is always associated with high $\delta^{18}O$ values in plagioclase. Much of the mineralogical replacement can be considered dissolution-reprecipitation associated with static hydration of the rocks, and the $^{18}O/^{16}O$ effects associated with these mineralogical replacements is highly variable and dependent on the quantity of secondary minerals ($\approx$ quantity of external fluid involved?).

Deformation and $^{18}O/^{16}O$ depletions

Many of the dredged gabbros exhibit high-temperature deformation textures. Several workers have noted a relationship between the amounts of various metamorphic minerals and the deformation (VANKO and BATIZA, 1982; BATIZA and VANKO, 1985; STAKES and VANKO, 1986; ITO and CLAYTON, 1983). Within the set of amphibolitized gabbros from the dredged Indian Ocean rocks, several samples (*e.g.* ANTP125-1; CIR97ZZ) have textures that suggest early high-temperature ductile deformation that has been subsequently obscured by metamorphic replacement. The best example of this is ANTP125-1, in which even the pyroxene has been partially recrystallized. The plagioclase and pyroxene from this sample are the *most* ^{18}O-depleted of any of the dredged samples.

The ^{18}O depletions in the pyroxenes from these amphibolitized gabbros are likely related to recrystallization under dynamic conditions, although some of the isotopic effects may also be attributable to amphibole impurities in the mineral separates. This is in contrast to the lack of isotopic exchange observed in the pyroxene separates from the undeformed gabbros. Samples that exhibit evidence of brittle deformation, possibly post-dating ductile deformation (*e.g.* CIR97X), show more extensive hydrous alteration, with no relict pyroxene. These correlations of metamorphic replacement, isotopic exchange, and deformation together suggest that high-temperature shear zones play a central role in providing the pathways for seawater to penetrate into the lower oceanic crust.

Stratigraphic control on $^{18}O/^{16}O$ and deformation

The Site 735B drillcore samples provide an unsurpassed opportunity to assess the relationship between major shear zones and penetration of seawater into the lower oceanic crust. The relationship between deformation and mineralogical alteration was observed on every scale. Even the smallest volume of hydrous alteration minerals in a single thin section can be observed to be associated with crosscutting healed microfractures (STAKES *et al.,* 1991). The deformation index (Textural type, Fig. 1), quantity of veins, and depletions in whole-rock $\delta^{18}O$ are all roughly coherent.

In the upper half of the core, the crosscutting vein network is consistently orthogonal to the metamorphic foliation and correlated with the final stages of extensional deformation. The host rock for this deformation-related vein network is consistently depleted in ^{18}O. The veins in the upper half of the core are mostly also depleted in ^{18}O, with the few high-^{18}O vein minerals probably a result of deposition at lower temperatures. The significant oxygen isotopic shifts in the upper half of the drillcore are clearly related to deformation-enhanced penetration of seawater and subsequent metamorphic replacements. The stratigraphic relationships of the ODP drillcore permit us to associate the textural deformation and isotopic exchange effects to the existence of major listric normal faults (CANNAT *et al.,* 1991a,b; DICK *et al.,* 1991).

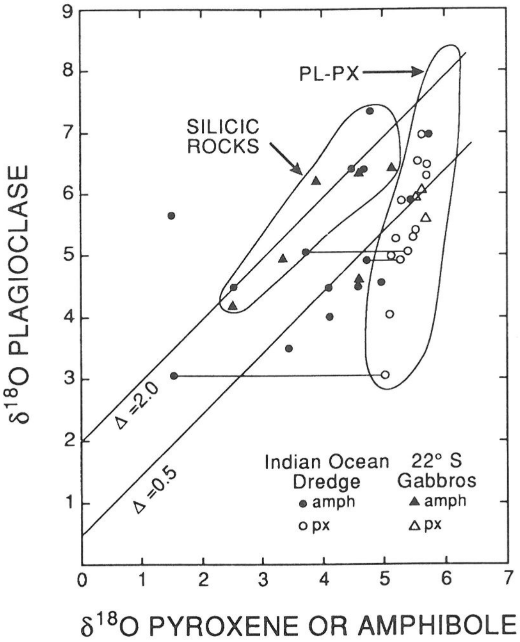

FIG. 2. Oxygen isotopic compositions for coexisting pairs of plagioclase and either pyroxene (open symbols) or amphibole (filled symbols) for dredged rocks. Unperturbed igneous rocks would fall close to the high-temperature equilibrium fractionation line indicated by $\Delta = 0.5$, and lower temperatures of equilibration would be expected to have higher Δ values (*e.g.* the $\Delta = 2$ line). Silicic rocks include diorites, plagiogranites, aplites, and a quartz monzonite. PL-PX = plagioclase-pyroxene pairs, which form a steeply dipping array as a result of depletion of ^{18}O in the plagioclase while largely preserving igneous $\delta^{18}O$ values of the pyroxene.

Plagioclase-pyroxene/amphibole $^{18}O/^{16}O$ fractionations

Isotopic compositions for plagioclase coexisting with pyroxene or amphibole for (a) dredged samples and (b) drillcore samples are provided in Figs. 2 and 3, respectively. Plagioclase-pyroxene fractionations at igneous temperatures are about 0.5 per mil, and the data-points for fresh gabbroic rocks would be expected to fall near such an equilibrium line, as shown in the two diagrams. Equilibrium at some lower temperature would similarly produce a linear array above this line (larger Δ values). Plagioclase-pyroxene pairs (open symbols) on both plots lie along a steeply dipping array that represents ^{18}O depletion of plagioclase together with virtual preservation of the igneous $\delta^{18}O$ values of the coexisting pyroxene. Such trends are characteristic of open-system isotopic exchange in hydrothermally altered plutonic rocks (GREGORY and TAYLOR, 1981; TAYLOR, 1974, 1977, 1983; TAYLOR and FORESTER, 1979; GREGORY and CRISS, 1986) and are the most sensitive indicators of water-rock interactions.

Very few of the plutonic rocks studied (only the 22°S olivine gabbros and a few drillcore samples) have $\delta^{18}O$ values characteristic of fresh, unaltered gabbroic rocks, even in those samples which contain only modest quantities of secondary minerals. Only two of the drillcore samples have igneous $\delta^{18}O$ values and plagioclase-pyroxene pairs that fall along the $\Delta = 0.5$ per mil "equilibrium line." In the remaining samples both the plagioclase and the pyroxene are depleted ^{18}O. The "equilibrium pairs" with ^{18}O-depleted pyroxene likely are a result of

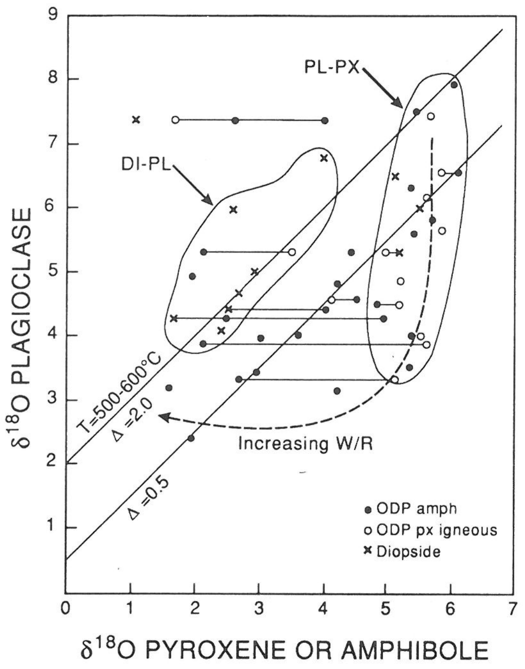

FIG. 3. Oxygen isotopic compositions for coexisting pairs of plagioclase and either pyroxene (open symbols), diopside (X's) or amphibole (filled symbols) for samples from ODP Leg 118 Hole 735B. PL-PX and lines for $\Delta = 0.5$ and $\Delta = 2.0$ are the same as in Fig. 2, with $\Delta = 0.5$ representing igneous temperatures and $\Delta = 2.0$ indicating metamorphic temperatures. DI-PL = coexisting secondary diopside and plagioclase. Dashed line tracks progressive alteration of the gabbroic rocks: (a) at low water/rock ratios (W/R) the only evidence of alteration is the preferential ^{18}O depletion of plagioclase relative to pyroxene; (b) with increasing W/R, pyroxene is increasingly replaced by low-^{18}O amphibole; and (c) at high W/R veins are filled with plagioclase, hornblende, and/or diopside in apparent isotopic equilibrium at metamorphic temperatures.

enhanced isotopic exchange associated with ductile deformation and hydrothermal recrystallization at very high temperatures. For plagioclase-pyroxene pairs that fall below the "equilibrium line," amphibole is typically depleted in ^{18}O compared to pyroxene.

Some plagioclase-amphibole pairs (filled symbols) also fall along the same limits of steeply dipping arrays as observed for plagioclase-pyroxene. However, most of the plagioclase-amphibole pairs, especially in the drillcore samples, fall either near the igneous equilibrium band or in the region that represents lower temperatures of equilibration (above and to the left of the $\Delta = 0.5$ line). The apparent close approach to equilibrium of the plagioclase-amphibole pairs underscores the observation that, in the absence of dynamic recrystallization, the only mafic minerals that monitor the fluid $\delta^{18}O$ value are those that are new metamorphic minerals; the unrecrystallized pyroxene does not undergo any appreciable isotopic exchange. This isotopic exchange/replacement apparently begins at near-igneous temperatures, consistent with the Δ values of the few plagioclase-recrystallized pyroxene pairs.

Most plagioclase-amphibole pairs plot within the field between the $\Delta = 0.5$ and $\Delta = 2.0$ lines. Points that fall above and to the left of this field are samples that either (1) contain plagioclase that has been enriched in ^{18}O at low temperatures or (2) are fractionated rocks from the MAR. The plagioclase-diopside (metamorphic) pairs from the Site 735B drillcore samples fall within this same field, except for the three veins with strongly ^{18}O-enriched plagioclase. Such samples are not thought to represent equilibrium pairs. The diopside coexisting with the high-^{18}O plagioclase is frequently partially altered to actinolite, suggesting a low-temperature overprint for both minerals.

Plagioclase-diopside fractionation has been experimentally calibrated by MATTHEWS *et al.* (1983), using the formula

$$\Delta(\text{plag-px}) = 1.58 - 1.09(\beta)\ 10^6 T^{-2},$$

where β is the mole fraction of An in the plagioclase.

The precise temperature estimate is dependent upon the composition of the plagioclase assumed to be in equilibrium with the diopside. Analyzed plagioclase compositions in this work vary from An = 30 to An = 0, but the mineral grains frequently show evidence of zonation and late low temperature alteration. For the purpose of this calculation, a plagioclase composition of An = 20 is used, consistent with the least altered plagioclase-diopside veins. Based on this composition, estimated temperatures of formation vary from 622 to 265°C (excluding values for plagioclase with $\delta^{18}O > +6.5$). More sodic plagioclase compositions would result in higher temperature estimates.

Using the above temperatures of formation and the $\Delta(\text{plag-}H_2O)$ fractionation equation from O'NEIL and TAYLOR (1967), the isotopic composition of the fluid phase can be calculated. The fluid $\delta^{18}O$ and the temperatures of formation are plotted in Fig. 4. The calculated fluid compositions vary from near seawater ($\delta^{18}O = +0.4$) at low temperatures to ^{18}O-enriched values ($\delta^{18}O = +4.6$) at the highest temperatures. The range of temperatures and isotopic compositions suggests mixing between seawater and either a strongly ^{18}O-shifted hydrothermal endmember or a hydrous fluid exsolved from the magma.

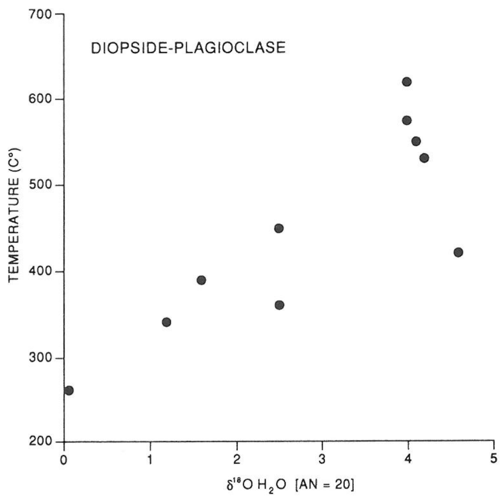

FIG. 4. Calculated isotopic temperatures of formation of diopside-plagioclase veins based on the calibration curves of MATTHEWS (1983) and corrected to an average plagioclase composition of An20. The isotopic composition of the aqueous fluid coexisting with each pair is calculated from the temperature and the plagioclase $\delta^{18}O$ value, using the equilibrium equation from O'NEIL and TAYLOR (1967).

Hydrogen isotope compositions

The D/H ratios of the amphibole separates provide additional evidence about the nature of the aqueous fluids that exchanged with these rocks. Using the hornblende-water fractionation curve of SUZUOKI and EPSTEIN (1976), the range of δD values in Fig. 5 for "seawater metamorphism" would require temperatures of formation of about 400 to 500°C. Lower values of δD require either lower temperatures of formation (down to 300°C) or a fluid depleted in deuterium compared to seawater. A lower temperature of formation is discounted as an explanation for the low δD hornblende values, as these samples are characterized by euhedral brown to green aluminous hornblende petrographically and chemically similar to hornblendes in the other samples. The alternative is that these hornblendes record the presence of a different hydrous fluid. This hydrous fluid could have been: (1) "primary" (derived from a deep-seated magmatic source); (2) a metamorphic dehydration water; or (3) water liberated from hydrous rocks as they are incorporated into a magma during assimilation, thereby mixing with any available magmatic water (see TAYLOR, 1986, and Fig. 5).

Primary hornblendes from most igneous rocks have δD values in the range −80 to −60 (TAYLOR and SHEPPARD, 1986). The low δD hornblendes from the Indian Ocean gabbros fall in a range intermediate between such "magmatic water" values and the "metamorphic water" values as defined from the other hornblende separates. This range of values could represent a mixture of hornblendes from magmatic and metamorphic origins. The δD of the H_2O in a magma (and presumably of its derivative fluid phase) can also be increased by isotopic fractionation during formation of methane (TAYLOR, 1986), and CH_4 has in fact been identified within fluid inclusions in these gabbros (VANKO and STAKES, 1991). The intermediate δD values could also result from a hybrid fluid derived from assimilation of rocks previously altered by seawater-hydrothermal fluids, a derivation supported by the petrographic evidence of partially digested xenoliths.

CONCLUSIONS

(1) The oxygen isotopic compositions of seafloor gabbros and their differentiates, representing portions of oceanic layer 3, record pervasive high-temperature interactions with seawater. Temperatures of metamorphism are typically in excess of 600°C, but most assemblages record equilibrium temperatures of 400–600°C. The range of temperatures estimated from plagioclase-diopside and plagioclase-hornblende pairs is identical for both metamorphic veins and late-stage silicic differentiates.

(2) Plagioclase-pyroxene pairs are rarely equilibrated except under conditions of dynamic recrystallization. Rather, plagioclase is preferentially de-

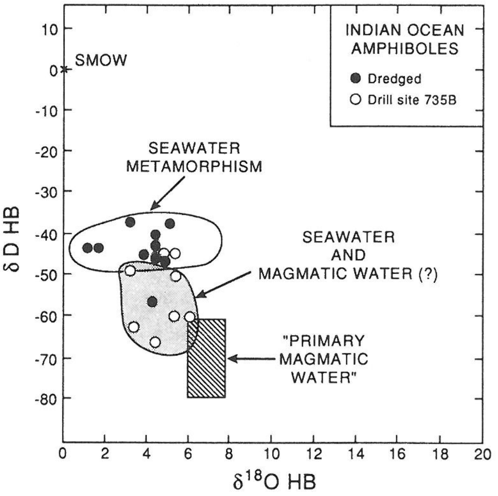

FIG. 5. Oxygen and hydrogen isotopic compositions of hornblende separates (HB) from Indian Ocean plutonic rocks. Primary magmatic hornblendes would be expected to fall into cross-hatched region.

pleted in ^{18}O, and pyroxene is either relict or is replaced by amphibole in equilibrium with the plagioclase. Many of the plutonic rocks exhibit textural evidence of local ductile deformation, commonly obscured by later hydrous alteration. The effects of plagioclase ^{18}O-depletion, hornblende replacement of pyroxene, and isotopic equilibration of hornblende and plagioclase can be correlated with aqueous fluid-rock ratios.

(3) The penetration of fluid into the lower oceanic crust and the degree of isotopic equilibration of the coexisting minerals are directly correlated with increased deformation and increased local permeability. Evidence of assimilation of metagabbro by late-stage intrusives suggests that high-grade metamorphism and the latest-stage magmatic processes may be contemporaneous in time (cooling history) and space (permeable ductile shear zones).

(4) Gabbros from ODP Leg 118, Site 735B, comprise the first drillcore samples from intact oceanic layer 3. Plagioclase-diopside veins from the lower portions of this core record temperatures of formation up to 620°C from an aqueous fluid strongly enriched in ^{18}O (up to 4.5 per mil) compared to normal seawater.

(5) Hydrogen isotopic analyses of hornblende separates fall into two groups: one comprised solely of a seawater-metamorphic origin, and a second group that suggests the presence of mixing between a magmatically derived fluid that has a δD value at least 20 to 30 per mil lighter than the seawater-derived metamorphic fluid. It is possible that some of the magmatic fluid itself may ultimately have been derived from seawater.

(6) Volumetrically, the most important hydrothermal-metamorphic processes recorded by the mineral assemblages and isotopic compositions of the plutonic rocks took place under amphibolite-facies conditions. Greenschist and zeolite grade minerals are only found locally, suggesting that pervasive fluid penetration diminished as the temperatures declined.

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