15. CHEMISTRY AND GEOTHERMOMETRY OF SECONDARY MINERALS FROM THE DEEP SHEETED DIKE COMPLEX, HOLE 504B[1]

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ABSTRACT

Dolerites sampled from the lower sheeted dikes from Hole 504B during Ocean Drilling Program Legs 137 and 140, between 1562.4 and 2000.4 mbsf, were examined to document the mineralogy, petrography, and mineral parageneses associated with secondary alteration, to constrain the thermal history and composition of hydrothermal fluids. The main methods used were mineral chemical analyses by electron microprobe, X-ray diffraction, and cathodoluminescence microscopy. Temperatures of alteration were estimated on the basis of single and/or coexisting mineral chemistry.

Permeability is important in controlling the type and extent of alteration in the studied dike section. At the meter-scale, intervals of weakly altered dolerites containing fresh olivine are interpreted as having experienced restricted exposure to hydrothermal fluids. At the centimeter- or millimeter-scale, alteration patches and extensively altered halos adjacent to veins reflect the permeability related to intergranular primary porosity and cracks. Most of the sheeted dike alteration in this case resulted from non-focused, pervasive fluid-rock interaction.

This study confirms and extends the previous model for hydrothermal alteration at Hole 504B: hydrothermal alteration at the ridge axis followed by seawater recharge and off-axis alteration. The major new discoveries, all related to higher temperatures of alteration, are: (1) the presence of hydrothermal plagioclase (An_{80-95}), (2) the presence of deuteric and/or hydrothermal diopside, and (3) the general increasing proportion of amphiboles, and particularly magnesio-hornblende with depth.

We propose that the dolerites at Hole 504B were altered in five stages. Stage 1 occurred at high temperatures (less than 500° to 700°C) and involved late-magmatic formation of Na- and Ti-rich diopside, the hydrothermal formation of Na, Ti-poor diopside and the hydrothermal formation of an assemblage of An-rich plagioclase + hornblende. Stage 2 occurred at lower temperatures (250°–320°C) and is characterized by the appearance of actinolite, chlorite, chlorite-smectite, and/or talc (in low permeability zones) and albite. During Stage 3, quartz and epidote precipitated from evolved hydrothermal fluids at temperatures between 310° and 320°C. Anhydrite appeared during Stage 4 and likely precipitated directly from heated seawater. Stage 5 occurred off-axis at low temperatures (250°C) with laumontite and prehnite from evolved fluids.

INTRODUCTION

Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP) Hole 504B has come to be regarded as a reference section through the upper oceanic crust (Anderson et al., 1982; Becker, Sakai, et al., 1989). Hole 504B is located in 5.9 Ma crust, 200 km south of the intermediate-spreading-rate Costa Rica Rift in the eastern Pacific Ocean. The hole was drilled through 274.5 m of sediment, a 571.5-m volcanic section, a 209-m transition zone, and 945 m into the sheeted dike complex (Fig. 1). Study of the secondary mineralogy, stable isotopic compositions, and fluid inclusions led to a model for the hydrothermal history of the upper 1500 m of the crust at Site 504 (Alt et al., 1985, 1986a, b, 1989a, b; Honnorez et al., 1983; Laverne et al., 1989). The volcanic section underwent low temperature (<100°C) oxidizing alteration at high water/rock ratios (at ≈100), whereas the lower volcanics were affected by low temperature alteration under more restricted circulation and more reducing conditions, at lower water/rock ratios (≈10). There is an abrupt change to the underlying transition zone and sheeted dikes, which were altered to greenschist facies minerals at higher temperatures (250°–380°C). At the spreading axis, hydrothermal fluids upwelling along fractures in the relatively impermeable dikes mixed with larger volumes of cooler seawater circulating in the more porous and permeable volcanic section, causing the formation of a stockwork-like sulfide mineralization at 900–929 mbsf in the transition zone, and resulting in the formation of a sharp alteration boundary in the crust that coincides with the lithologic boundary. Evolution of hydrothermal fluids resulted in deposition of a sequence of secondary minerals filling fractures in the sheeted dikes: first chlorite and actinolite formed from more seawater-like fluids, followed by epidote, quartz, and sulfides from more evolved fluids. Later recharge of seawater into host rocks led to the precipitation of anhydrite in veins, and finally, off-axis circulation of highly evolved fluids at lower temperatures (<250°C) resulted in the formation of zeolites in veins and rocks of the upper dike section, and zeolites and carbonates in the volcanics. Trends toward increasing amounts of actinolite, increasing alteration of pyroxene, and decreasing alteration of plagioclase were recognized in samples from Leg 111 (1075.5–1287.5 mbsf), and suggested generally increasing temperatures of alteration downward in the dikes (Alt et al., 1989b).

At a depth of 2000.4 m below seafloor (mbsf) at the end of Leg 140, the hole is considered to be very close to the lithologic boundary, which many think separates sheeted dikes of the upper crust from gabbroic rocks in the lower crust. The nature of this boundary is thought to be extremely important in our understanding of how oceanic hydrothermal systems operate. Studies of black smokers typically estimate the depth of the "reaction zone" as 2 km (e.g., Von Damm et al., 1985), and this is where the source of black smoker fluids might be found. Legs 137 and 140 deepened Hole 504B by drilling 438 m more in the sheeted dike complex, so that the total thickness of cored sheeted dikes now exceeds 945 m.

This paper documents the mineralogy, petrography, and mineral parageneses associated with secondary alteration of the lower sheeted dikes from Hole 504B drilled during Legs 137/140, to constrain the thermal history and the compositions of hydrothermal fluids. These data are combined and compared with previous results from the upper

Figure 1. Distribution of secondary minerals with depth in Hole 504B (modified from Shipboard Scientific Party, 1992b). Lithostratigraphy, seismic stratigraphy, and drilling legs also shown (Anderson, Honnorez, Becker, et al., 1985; Shipboard Scientific Party, 1988, 1992a, b). ML smect-chl = mixed-layer smectite-chlorite with dominant smectite; ML chl-smect = mixed-layer chlorite-smectite with dominant chlorite; Na-zeolite includes analcite, natrolite, stilbite, and epistilbite; Ca-zeolite includes laumontite, heulandite, and scolecite.

sheeted dikes in Hole 504B and ophiolites to further constrain hypotheses of hydrothermal alteration of oceanic crust.

METHODS

Subsequent to shipboard studies, about 250 thin sections from the Legs 137/140 cores were prepared at various institutions. Mineral chemistry was obtained by electron microprobe at Paris (= P) and Brest (= B; France), Padova (= V; Italy), and Atlanta (= A) and Ann Arbor (= AA; USA). All analyses used wavelength dispersive spectrometers and employed well-characterized natural and synthetic standards. Results were processed into mineral chemical formulae using standardized recalculation schemes. Backscattered electron imaging and energy-dispersive X-ray analyses were also used for qualitative chemical analyses and mineral identification.

X-ray diffraction identification of some minerals, as well as preliminary high resolution transmission electron microscope (HRTEM) observations and analyses of secondary phases, were performed in Marseille. Cathodoluminescence microscopy was carried out in Atlanta using a 30 keV cold cathode luminoscope.

Core recovery during Legs 137/140 was approximately 11%; thus the potential for non-representative sampling of the deep sheeted dike section must be kept in mind. The unsampled sections may be randomly distributed, in which case the recovered samples likely are adequately representative. On the other hand, the unsampled sections may be biased toward highly fractured or otherwise crumbly units. The depth of each sample studied is constrained by the known depth of the top and bottom of each cored interval and the position of the sample in the recovered section. In this paper, the sample depths have

been calculated using the method proposed by Agrinier and Agrinier (in press). In most plots involving downhole depth, the symbol sizes exceed the depth uncertainty.

PETROGRAPHIC SUMMARY

Detailed petrographic descriptions of the alteration of this section of dikes are presented in the Leg 140 *Initial Reports* (Shipboard Scientific Party, 1992b), and are summarized below.

Primary Igneous Features

Fresh, unaltered dolerite contains plagioclase + clinopyroxene + titanomagnetite ± olivine ± spinel, and has a tholeiitic bulk composition. Its grain size varies from aphanitic in chilled margins to as much as 1.9 mm in the interior of some dikes. There is an overall increase in the maximum grain size with depth, although numerous local variations occur. Olivine has compositions of Fo_{86-88}, primary clinopyroxene may be either Cr-diopside or augite, and primary plagioclase is generally labradorite An_{60-75}. Some recovered dolerites contain sodic plagioclase, quartz, and apatite in interstitial areas, due to late magmatic in-situ crystallization. The dolerite is generally primitive, with Mg* [molar $100Mg/(Mg + Fe^{2+})$] around 65.

Alteration Features

Overprinting all dolerite samples is a pervasive background alteration, characterized by 5%–40% replacement of primary minerals by secondary phases. Clinopyroxene is replaced by amphibole, and much more rarely by secondary clinopyroxene. Plagioclase may be replaced by one or more generations of secondary plagioclase, anhydrite, laumontite, epidote, chlorite, or some combination of these minerals. Olivine is variably replaced by chlorite, mixed-layer chlorite-smectite, talc, quartz, sulfides, magnetite, and hematite. Titanomagnetite is replaced by titanite.

In addition to pervasive background alteration, many dolerite samples contain alteration patches and secondary veins with or without adjacent alteration halos. The patches are regions, usually 1–3 cm in size, but up to about 10 cm across, of highly altered (up to 100%) dolerite. Patches can be spherical, ovoid, or variably elongated: their irregular and variable shapes appear to be independent of veins or any remaining primary features of the dolerite. These patches are apparently zones where hydrothermal solutions had increased access to the dolerite, and were likely initiated within zones of original high primary porosity (e.g., gas vesicles, segregation vesicles, diktytaxitic voids, etc.). Many patches surround 0.1–2 mm amygdules filled with chlorite and actinolite, and some surround millimeter-scale spherical amygdules with crudely concentric mineral fillings (e.g., actinolite, chlorite, laumontite, and epidote). Larger patches may represent coalescing of smaller patches and continued growth of the alteration zones at the expense of the surrounding dolerite.

Hydrothermal veins, on the order of 1 mm wide, generally consist of actinolite, chlorite, or actinolite + chlorite, all of which may also contain small amounts of apatite and titanite. Less abundant veins include quartz, epidote, prehnite, laumontite, heulandite (stilbite?), and anhydrite. Detailed descriptions of veins are given in the Leg 140 *Initial Reports* (Shipboard Scientific Party, 1992b) and in Tartarotti et al. (this volume).

Alteration halos adjacent to veins are usually characterized by extensive recrystallization (typically 40%–90%). They can be either simple or compound, the latter commonly consisting of a dark interior zone close to the vein and a lighter outer zone. Primary clinopyroxene in the alteration halos is partly replaced by amphibole, and primary plagioclase is partly replaced by one or more generations of secondary plagioclase (anorthite, oligoclase, or albite). Halos also contain accessory secondary titanite, chlorite, and apatite.

Alteration Distribution

Whereas there is a general trend toward increasing extent of alteration and increasing proportion of amphibole with depth in the dike section, the extent of alteration varies considerably through the sheeted dikes.

The detailed vein log of Legs 137/140 cores shows that lithologic units with the highest vein abundances are almost invariably associated with chilled margins or fine-grained dolerites (Shipboard Scientific Party, 1992b). This suggests that millimeter-scale fractures, thought to result from thermal contraction, were more prevalent near dike margins. Alteration patches, on the other hand, are actually more common in the coarser grained dike interiors. Both veins and alteration patches occur throughout the Legs 137/140 dike section, showing no apparent depth control.

Unaltered olivine relics are present in rocks from 1705 to 1733 mbsf and sporadically at greater depths, whereas there is only one documented occurrence of fresh olivine in the upper dike section (Becker, Sakai, et al., 1988).

MINERALOGY

In this section we describe and present chemical data on most major hydrothermal minerals, and we highlight the resulting constraints on the physico-chemical conditions of hydrothermal alteration.

Secondary Clinopyroxene

Secondary clinopyroxene has been distinguished in seven samples from Legs 137/140. Two types were identified: (1) Ti- and Na-rich diopside-hedenbergite in two samples between 1595 and 1619 mbsf, and (2) diopside without anomalous Ti or Na contents in five samples from 1573.1 to 1999.1 mbsf.

Samples 137-504B-177R-1, 11–15 cm (Piece 4A) and 137-504B-180M-1, 74–78 cm (Piece 7) (Pl. 1) each contain a 0.2-mm-thick vein composed of actinolite and euhedral titanite, plus chlorite at the center in Sample 137-504B-177R-1, 11–15 cm (Piece 4A). All of the host-rock pyroxene crystals along the vein wall are replaced by a thin (0.05 mm) layer of bright-green pyroxene (Pl. 1). In Sample 137-504B-177R-1, 11–15 cm (Piece 4A), this pyroxene changes texture toward the interior of the vein, grading into a colorless, granular form, then colorless and fibrous. Despite the variety of appearances, each of these minerals has a pyroxene stoichiometry. Their high Na_2O (up to 1.3 wt%), TiO_2 (up to 1.1 wt%) and Al_2O_3 (up to 3.3 wt%) concentrations (Table 1) clearly distinguish them from primary clinopyroxene (Fig. 2). In contrast to primary clinopyroxene, these secondary pyroxenes contain no Cr_2O_3 (Fig. 3). Secondary clinopyroxene from Sample 137-504B-177R-1, 11–15 cm (Piece 4A), is diopside with variable FeO, whereas that from Sample 137-504B-180M-1, 74–78 cm (Piece 7), varies from diopside to hedenbergite, according to the classification of Morimoto (1988) (Fig. 4). A 30-mm euhedral colorless clinopyroxene crystal occurs within a 0.6-mm-wide vein of hornblende and actinolite, with chlorite filling the center of the vein in Sample 137-504B-177R-1, 11–14 cm (Piece 4A). This pyroxene does not apparently replace primary clinopyroxene, but it is clearly secondary and exhibits patchy compositional zoning of diopsidic composition (Table 1). Both hornblende and greenish secondary pyroxene also partly replace igneous clinopyroxene along the walls of this vein, although these secondary minerals do not occur in mutual contact.

Diopside, without anomalous Na concentrations, occurs as very discrete colorless grains recrystallized from igneous clinopyroxene in veins and patches (e.g., Samples 140-504B-189R-2, 100–104 cm (Piece 14), 140-504B-205R-1, 13–16 cm (Piece 1), and 140-504B-237R-1, 24–26 cm (Piece 7), or new crystals nucleated among amphibole in veins (Sample 137-504B-176R-1, 15–17 cm (Piece 3). The compositions fall mainly above the line separating "diopside" from "augite" (i.e., 45 mol% wollastonite, and for simplicity, we refer to all

Figure 2. Plot of Na_2O (wt%) vs. wollastonite component (mol%) for selected clinopyroxenes from Hole 504B, Legs 137/140. Most magmatic clinopyroxenes contain less than about 0.4 wt% Na_2O, whereas hydrothermal clinopyroxenes generally have greater than about 0.4% Na_2O.

Figure 3. Plot of Cr_2O_3 (wt%) vs. wollastonite component (mol%) for selected clinopyroxenes from Hole 504B, Legs 137/140. Magmatic clinopyroxenes contain up to about 1.0 wt% Cr_2O_3 at wollastonite compositions generally less than 45 mol%. Hydrothermal clinopyroxenes, in contrast, invariably have less than 0.2 wt% Cr_2O_3 at wollastonite compositions generally greater than about 45 mol%.

Figure 4. Pyroxene quadrilateral with Hole 504B, Legs 137/140 clinopyroxene compositions (same symbols as Figs. 2 and 3). End-member abbreviations are Di = diopside, Hd = hedenbergite, En = enstatite, and Fs = ferrosilite. The field of magmatic clinopyroxene (after McNeill, this volume) is represented.

of these as "diopside". Colorless fine-grained diopside, associated with scarce Mg-hornblende, also fills a 0.4-mm-thick vein in Sample 140-504B-213R-1, 3–6 cm (Piece 2). The diopside is enriched in Fe and Ca relative to primary augite (Fig. 4) and contains no detectable Cr_2O_3, in contrast to fresh augite (Fig. 3).

Amphibole

Amphibole is widespread throughout the Legs 137/140 section. It occurs as an alteration product of igneous clinopyroxene and filling

Table 1. Representative secondary clinopyroxene analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	Color	Occurrence	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr_2O_3	Cl	ZnO	Total
173R-1, 77–79	B2185	clss	m	52.71	0.14	0.78	11.63	0.26	12.73	21.75	0.18	0.01	0.04	0.00	0.00	100.23
176R-1, 15–17	A7	clss	amp vein cent	50.46	0.09	0.87	17.55	0.15	8.13	23.28	0.41	0.00	0.00	nd	nd	100.94
177R-1, 11–14	AA1	clss	amp vein cent	51.95	0.04	0.18	7.82	0.13	14.42	24.78	0.45	0.01	0.00	nd	nd	99.78
177R-1, 11–15	B2109	gr	amp vein wall	52.87	0.05	0.77	13.29	0.25	11.76	21.67	0.07	0.00	0.03	0.03	0.18	100.97
	B2112	gr	amp vein wall	54.58	0.21	0.20	6.99	0.17	14.59	24.44	0.30	0.02	0.00	0.00	0.00	101.50
	B2114	gr	amp vein wall	51.12	1.15	1.50	12.25	0.15	11.59	21.96	1.26	0.00	0.04	0.00	0.00	101.02
	B2122	gr	amp vein wall	51.08	0.79	1.01	12.50	0.28	11.40	22.65	0.86	0.00	0.00	0.00	0.00	100.57
180M-1, 74–78	B5061	clss	m	53.02	0.28	2.79	5.34	0.28	18.38	19.68	0.19	0.00	0.65	nd	nd	100.62
	B5062	clss	m	53.85	0.17	2.44	5.38	0.09	18.69	19.08	0.17	0.02	0.57	nd	nd	100.47
	B5063	gr	amp vein wall	49.31	0.29	2.66	16.33	0.28	8.26	22.37	0.93	0.00	0.00	nd	nd	100.42
	B5064	gr	amp vein wall	51.27	0.14	1.10	14.52	0.31	10.00	23.30	0.55	0.01	0.03	nd	nd	101.22
	B5065	gr	amp vein wall	49.50	0.44	2.73	14.60	0.10	9.15	22.21	1.03	0.00	0.00	nd	nd	99.76
	B5071	gr	amp vein wall	50.96	0.07	1.18	14.84	0.34	9.44	22.91	0.74	0.00	0.00	nd	nd	100.49
	B5072	gr	amp vein wall	50.17	0.32	1.89	15.14	0.41	8.76	22.74	0.74	0.00	0.00	nd	nd	100.16
	B5075	gr	amp vein wall	48.15	0.60	3.33	16.13	0.23	7.77	22.10	1.11	0.00	0.07	nd	nd	99.49
	B5077	gr	amp vein wall	48.76	0.22	2.85	16.62	0.40	7.80	22.08	1.09	0.05	0.08	nd	nd	99.94
	B5079	gr	amp vein wall	48.51	0.42	3.12	16.68	0.19	7.94	21.81	1.03	0.01	0.00	nd	nd	99.71
	B5080	gr	amp vein wall	50.04	0.25	1.66	15.07	0.35	8.69	22.53	0.86	0.00	0.06	nd	nd	99.52
189R-1, 105–106	B2016	clss	m	52.83	0.35	2.65	6.67	0.17	18.33	18.03	0.15	0.00	0.25	0.00	0.13	99.56
189R-2, 76–79	B2164	clss	m	52.49	0.34	2.84	5.05	0.25	18.00	20.28	0.19	0.02	0.63	0.01	0.00	100.10
189R-2, 100–104	A47	clss	amp+chl patch	51.86	0.05	0.32	11.90	0.31	12.98	21.68	0.26	0.02	0.05	nd	nd	99.43
	A52	clss	m	51.16	0.40	2.70	0.20	5.97	0.15	16.26	21.42	0.10	0.00	nd	nd	98.36
200R-2, 101–104	B2104	clss	m	51.73	0.63	3.65	7.05	0.08	16.09	21.15	0.20	0.00	0.22	0.00	0.00	100.80
205R-1, 13–16	A68	clss	recr in halo	52.23	0.21	1.59	7.29	0.27	14.89	23.08	0.22	0.00	0.15	nd	nd	99.93
212R-1, 61–65	B5094	clss	m	51.54	0.51	3.08	7.37	0.24	16.48	20.31	0.19	0.00	0.00	0.00	0.00	99.72
	B5092	clss	m	51.99	0.53	2.74	0.06	8.78	0.38	16.33	19.50	0.18	0.00	nd	nd	100.49
213R-1, 3–6	V1023	clss	vein (alone)	53.51	0.17	1.90	14.30	0.38	13.82	16.11	0.32	0.03	0.02	nd	nd	100.56
	V1029	clss	vein (alone)	53.41	0.18	0.70	12.46	0.39	13.91	18.75	0.14	0.01	0.00	nd	nd	99.95
225R-1, 126–129	B5042	clss	m	51.99	0.53	2.74	8.78	0.38	16.33	19.50	0.19	0.00	0.06	0.05	0.00	100.55
226R-1, 99–102	B2072	clss	m	49.64	1.05	1.63	18.55	0.61	11.74	16.84	0.53	0.12	0.06	0.18	0.00	100.95
237R-1, 24–26	B3008	clss	m	51.99	0.45	3.31	7.20	0.20	17.88	18.71	0.23	0.04	0.06	0.00	0.00	100.07
	A105	clss	recr in halo	52.65	0.00	0.57	11.64	0.40	11.56	21.71	0.10	0.00	0.03	nd	nd	98.66

Notes: clss = colorless; gr = green; amp = amphibole; chl = chlorite; m = magmatic; recr = recrystallized; nd = not determined. The projected Wo´-En´-Fs´-Ac-Jd-FeCaTs-CrCaTs-AlCaTs values have been calculated according to Lindsley and Anderson (1983).

Table 1 (continued).

Core, section, interval (cm)	Si	Ti	Al	Cr	FeT	Fe^{3+}	Fe^{2+}	Mn	Mg	Ca	Na	K	Total	Wo	En	Fs	Wo′	En′	Fs′
173R-1, 77–79	1.983	0.004	0.035	0.001	0.366	0.003	0.363	0.008	0.714	0.877	0.013	0.000	4.001	44.6	36.3	19.0	43.6	37.4	19.0
176R-1, 15–17	1.943	0.003	0.039	0.000	0.565	0.075	0.490	0.005	0.467	0.960	0.031	0.000	4.013	48.1	23.4	28.5	46.1	27.0	26.9
177R-1, 11–14	1.937	0.001	0.008	0.001	0.244	0.111	0.133	0.004	0.801	0.990	0.033	0.000	4.019	48.5	39.3	12.2	45.3	48.8	5.8
177R-1, 11–15	1.993	0.001	0.034	0.001	0.419	−0.014	0.433	0.008	0.661	0.875	0.005	0.000	3.998	44.6	33.7	21.8	42.6	35.1	22.3
	1.995	0.006	0.009	0.000	0.214	0.009	0.205	0.005	0.795	0.957	0.021	0.001	4.002	48.6	40.3	11.1	48.4	41.1	10.4
	1.912	0.032	0.066	0.001	0.383	0.102	0.282	0.005	0.646	0.880	0.091	0.000	4.017	46.0	33.8	20.3	46.3	38.8	14.9
	1.926	0.022	0.045	0.000	0.394	0.091	0.303	0.009	0.641	0.915	0.063	0.000	4.015	46.7	32.7	20.6	46.0	37.9	16.1
180M-1, 74–78	1.919	0.008	0.119	0.019	0.162	0.017	0.145	0.009	0.992	0.763	0.013	0.000	4.003	39.7	51.5	8.8	35.5	56.5	7.9
	1.948	0.005	0.104	0.016	0.163	−0.010	0.173	0.003	1.008	0.740	0.012	0.001	3.999	38.7	52.7	8.7	34.2	56.7	9.2
	1.893	0.008	0.120	0.000	0.524	0.109	0.416	0.009	0.473	0.920	0.069	0.000	4.018	47.8	24.5	27.7	45.0	30.5	24.5
	1.940	0.004	0.049	0.001	0.460	0.077	0.383	0.010	0.564	0.945	0.040	0.000	4.013	47.8	28.5	23.7	46.1	33.0	20.9
	1.898	0.013	0.123	0.000	0.468	0.099	0.369	0.003	0.523	0.912	0.077	0.000	4.017	47.9	27.4	24.7	45.6	33.1	21.3
	1.945	0.002	0.053	0.000	0.474	0.081	0.393	0.011	0.537	0.937	0.055	0.000	4.013	47.8	27.4	24.7	46.9	31.6	21.5
	1.926	0.009	0.086	0.000	0.486	0.074	0.412	0.013	0.501	0.936	0.055	0.000	4.012	48.3	25.9	25.8	46.8	30.0	23.2
	1.867	0.017	0.152	0.002	0.523	0.120	0.403	0.008	0.449	0.918	0.083	0.000	4.020	48.4	23.7	28.0	45.2	30.3	24.5
	1.885	0.006	0.130	0.002	0.537	0.125	0.412	0.013	0.449	0.915	0.082	0.002	4.022	47.8	23.5	28.8	44.7	30.3	25.0
	1.878	0.012	0.142	0.000	0.540	0.116	0.424	0.006	0.458	0.905	0.077	0.000	4.019	47.4	24.0	28.6	44.2	30.3	25.5
	1.933	0.007	0.076	0.002	0.487	0.080	0.407	0.011	0.500	0.933	0.064	0.000	4.013	48.3	25.9	25.8	47.2	30.0	22.8
189R-1, 105–106	1.937	0.010	0.115	0.007	0.205	−0.004	0.208	0.005	1.002	0.708	0.011	0.000	3.999	36.9	52.2	10.9	33.0	55.6	11.4
189R-2, 76–79	1.909	0.009	0.122	0.018	0.160	0.028	0.131	0.008	0.975	0.790	0.013	0.001	4.005	40.9	50.5	8.7	36.5	56.4	7.1
189R-2, 100–104	1.968	0.001	0.014	0.001	0.378	0.048	0.329	0.010	0.734	0.882	0.019	0.001	4.009	44.0	36.6	19.4	42.7	40.2	17.1
	1.910	0.011	0.119	0.006	0.186	0.031	0.156	0.005	0.905	0.857	0.007	0.000	4.005	43.9	46.3	9.8	39.8	51.9	8.3
200R-2, 101–104	1.889	0.017	0.157	0.006	0.215	0.029	0.187	0.002	0.876	0.828	0.014	0.000	4.005	43.1	45.6	11.3	38.3	51.4	10.4
205R-1, 13–16	1.937	0.006	0.070	0.004	0.226	0.042	0.184	0.008	0.823	0.917	0.016	0.000	4.007	46.4	41.7	11.9	44.1	46.4	9.6
212R-1, 61–65	1.878	0.014	0.132	0.000	0.225	0.072	0.153	0.007	0.949	0.793	0.013	0.000	4.012	40.2	48.1	11.8	35.6	56.7	7.7
	1.912	0.015	0.119	0.002	0.270	0.030	0.240	0.012	0.895	0.768	0.013	0.000	4.005	39.5	46.0	14.5	36.1	50.8	13.1
213R-1, 3–6	2.002	0.005	0.084	0.001	0.447	−0.056	0.503	0.012	0.771	0.646	0.023	0.001	3.991	34.4	41.1	24.5	29.1	44.8	26.0
	2.008	0.005	0.031	0.000	0.392	−0.036	0.428	0.012	0.779	0.755	0.010	0.000	3.994	39.0	40.2	20.8	36.3	42.4	21.3
225R-1, 126–129	1.912	0.015	0.119	0.002	0.270	0.031	0.239	0.012	0.895	0.768	0.014	0.000	4.005	39.5	46.0	14.5	36.1	50.8	13.0
226R-1, 99–102	1.896	0.030	0.073	0.002	0.593	0.083	0.509	0.020	0.668	0.689	0.039	0.006	4.017	35.0	33.9	31.1	32.7	39.1	28.2
237R-1, 24–26	1.900	0.012	0.143	0.002	0.220	0.036	0.184	0.006	0.974	0.733	0.016	0.002	4.007	37.9	50.4	11.7	33.7	56.4	10.0
	2.019	0.000	0.026	0.001	0.373	−0.043	0.417	0.013	0.661	0.892	0.007	0.000	3.993	46.0	34.1	19.9	42.7	36.6	20.7

vugs, patches and veins (Pl. 1). Amphibole also occurs in interstitial groundmass areas, where no clear relationships to primary clinopyroxene can be identified.

Amphibole replacing clinopyroxene generally occurs as pseudomorphs or fine-grained fibers growing from the pyroxene crystal rims. In alteration patches amphibole is usually associated with chlorite, albite, titanite (± epidote, anhydrite and prehnite). Amphibole may also fill amygdules along with chlorite (Shipboard Scientific Party, 1992b).

Amphibole in veins occurs as both fine fibers and prismatic crystals. It may be associated with chlorite, laumontite, titanite, or apatite in compositionally complex veins. In a few veins, aggregates of needle-shaped amphibole have been observed, usually associated with laumontite. The vein-filling fibers exhibit no preferred shape orientation, although their elongation direction usually forms a high angle with the vein edges. These fibers are frequently deformed by kinking or bending. Along the vein walls, amphibole orientation is controlled by the cleavage orientation of clinopyroxene in the wallrock. Amphibole along vein walls partly replaces clinopyroxene, and it usually occurs as syntaxial overgrowths on pyroxene. In a few examples, more than one opening stage can be inferred from the textural arrangement of the vein-filling minerals (Tartarotti et al., this volume).

About 360 analyses of amphibole have been conducted by electron microprobe on the Legs 137/140 samples, and representative analyses are reported in Table 2. Structural formulas of amphibole and the partitioning iron were determined using the AMPHIBOL.EXE program (D. Hermitte, pers. comm., 1992), which assumes 15 total cations per formula unit, excluding potassium, and partitions ferrous and ferric iron to satisfy charge balance.

Following the nomenclature of Leake (1978), amphiboles have been classified into actinolite, Fe-actinolite, actinolitic hornblende, magnesio hornblende, edenite, and cummingtonite. Table 3 shows that most (60%) amphibole in the center and walls of veins is actinolite or Fe-actinolite, while most (70%) amphibole in the halos around veins is act-hornblende or mg-hornblende. Although not shown in Table 3, composite veins are characterized by actinolite in the center and hornblende along the walls. The groundmass away from veins and alteration halos is characterized by almost equal proportions of actinolite (actinolite + Fe-actinolite = 41%) and hornblende (act-hornblende + mg-hornblende = 44%). Amphibole in alteration halos around veins is locally iron-rich (Fe-actinolite; Table 2), whereas amphibole in the adjacent veins does not exhibit Fe-enrichment. Amphibole replacing clinopyroxene both in the halos and in the groundmass away from halos frequently exhibits higher Cr_2O_3 contents than does amphibole filling veins and patches (Table 2). The amphiboles generally have low chlorine concentration ranging from 0 to 0.10 wt% Cl, with a maximum of about 0.5 wt% Cl.

The maximum Al concentration at any depth is very irregular in the Leg 140 section, though occurrences of higher-Al amphiboles are more frequent than in the overlying dikes. The minimum Al concentration as a function of depth increases smoothly in the Legs 137/140 section, with the exception of the interval 1980–1990 mbsf, where low Al-amphiboles occur (Fig. 5).

The variation in amphibole composition with textural occurrence in the dolerite samples and the lack of major systematic downhole variation suggest that rock alteration is very heterogeneous in this section of the sheeted dike complex. One possibility is that amphibole composition has changed during the superposition of alteration stages occurring under different temperatures and/or different fluid compositions. If temperature was the controlling parameter, Mg-hornblende and actinolitic hornblende (associated with secondary Ca-plagioclase) formed in veins and in alteration halos around veins during early higher temperature hydrothermal alteration. Reactions may have been restricted to the vein and halo with little alteration of the host rock because the stage was too short-lived or because not enough fluid was available to react with the host rock. Halo development may have been restricted because of a generally low rock permeability. Subsequently,

as the system cooled, actinolite formed pervasively throughout the rock and in veins, whereas the previously formed hornblende was relatively stable so it did not react. Progressively cooling conditions are corroborated by the occurrence of laumontite filling the interstitial spaces in actinolite veins (Sample 140-504B-186R-1, 57–60 cm, Piece 10) and in actinolite-filled pore spaces in some alteration patches. Amphibole composition was also probably affected by fluid composition which may account for the local Fe-enrichment. Cr-enrichment in amphibole replacing clinopyroxene may be explained by the fact that amphibole inherited the composition of the original mineral phase (Tartarotti et al., this volume). Rock alteration is clearly very heterogeneous as a function of depth. The occurrence of high Al^{IV} contents accompanied by high TiO_2 contents in amphibole at specific depth values suggests that probably higher temperatures of equilibration were locally reached (Liou et al., 1974; Blundy and Holland, 1990).

Secondary Calcic Plagioclase, Albite, and Oligoclase

Secondary calcic plagioclase occurs in some extensively altered vein halos as incomplete replacement around the edges of primary igneous plagioclase laths, or total replacement of smaller laths enclosed in amphibole. The rims are compositionally distinct based upon differences in extinction angle, and they are charged with 10-mm-scale aqueous fluid inclusions.

Variations in plagioclase compositions (Table 4) and the textures of replacement are particularly easily observed with cathodoluminescence (abbreviated as CL hereafter; Mora and Ramseyer, 1992). Most vein halos are characterized by distinctly luminescing yellowish-green rims of secondary calcic plagioclase on the primary igneous plagioclase laths (Pl. 2). Electron microprobe analyses indicate that the primary plagioclase is typically labradorite, and that the fluid-inclusion-filled rims, typically bytownite and anorthite (Fig. 6), are uniformly more calcic than the cores.

Calcic plagioclase replacement rims are also chemically distinct from primary labradorite cores in minor elements. The most striking distinction is in MgO concentration, which is always lower in secondary plagioclase (Fig. 6). The concentration of FeO is also notably lower in secondary plagioclase.

In some vein halos, in many patches and in some rocks exhibiting strong background alteration, primary plagioclase laths are altered along microcracks to albite or oligoclase (Table 4). Secondary albite is characterized by little or no CL, thus it stands out in contrast to both the dull-CL primary plagioclase laths and the distinct-CL rims, both of which are cut by the albite when present. Fluid inclusions in albite are present but not as abundant as in the calcic rims. Other phases that also form vein-like replacement along fractures within plagioclase include laumontite, which has a dull reddish-orange CL color, and chlorite. These minerals cut both primary plagioclase and calcic rims, thus they appear to be related temporally to secondary albite. This is consistent with the occurrence of albite with laumontite and chlorite in patches of alteration interstitial to relict igneous plagioclase.

The occurrence of hydrothermal plagioclase that is more calcic than the associated igneous plagioclase has been recognized here for the first time in Hole 504B and, to our knowledge, for the first time in any oceanic rock. Calcic secondary plagioclase occurs in numerous cores between Cores 137-504B-174R and -229R. It has been positively identified at depths of 1577–1600, 1621, 1628, 1652, 1662, 1681, 1702–1760, 1778, 1795, 1818, 1828, 1875–1893, and 1912–1950 mbsf. Re-examination of a set of thin sections from Leg 111 reveals only one occurrence of calcic plagioclase rims, in Core 162R at a depth of approximately 1500 mbsf. The appearance of calcic plagioclase downhole correlates roughly with increases in, but not the first appearance of, both hydrothermal clinopyroxene and magnesio-hornblende.

Chlorite and Chlorite-Smectite

Chlorite occurs in veins, either alone or associated with actinolite. Common composite chlorite-actinolite veins are commonly com-

Figure 5. Plot of Al^{IV} vs. depth for amphiboles from Hole 504B, Legs 137/140. Note the broad trend of slightly higher Al^{IV} with depth, and the higher-frequency variations associated with individual samples (e.g., the high Al-amphiboles at 1630, 1760, 1820, 1929, and 1980 mbsf, and the low-Al ones at 1600 and 1980 mbsf).

Figure 6. Results of electron microprobe analysis of feldspars from alteration patches or vein halos. In each case, the cathodoluminescent character of the analyzed spot was determined, because primary unaltered igneous plagioclase cores are nonluminescent, whereas secondary, inclusion-filled replacement rims luminesce brightly. The primary igneous plagioclase (closed symbols) is typically bytownite (An$_{70-90}$) and contains 0.1%–0.5 wt% MgO. The secondary plagioclase rims (open symbols) are more calcic bytownite and anorthite, and contain <0.1 wt% MgO. Tie lines connect analyses taken within several tens of microns across a core-rim boundary. A similar plot for FeO shows a similar situation, although the FeO concentrations of the two groups overlap somewhat. CL refers to luminescent rims of plagioclase exhibiting cathodoluminescence.

posed of chlorite where they cut plagioclase and by actinolite where they cut across augite. Chlorite commonly replaces olivine or the rim of olivine phenocrysts whose core is replaced by a mixed-layer chlorite-smectite (Pl. 2).

The chemical compositions of some representative chlorite and mixed-layer chlorite-smectites are given in Table 5. The optical properties of these minerals reflect their chemical composition and structure: chlorite is light green, pleochroic, and shows anomalous brown or purple interference colors or "normal" blue-gray with crossed polars, whereas mixed-layered chlorite-smectite is pleochroic darker green or brownish to yellowish green, with higher birefringence. Analyses plot in the pycnochlorite and diabantite fields of Hey's (1954) classification (Fig. 7). Most of the analyses plot in the fields of Legs 83 and 111 chlorites, but some are slightly enriched in iron.

When plotted on a (Si + Al^{tot} + Fe + Mg) vs. (Al^{tot}) diagram (Schiffman and Fridleifsson, 1991), the Legs 137/140 data plot along the saponite-chlorite trend although most of the points are concentrated around the chlorite end-member.

The percentage (X) of pure chlorite in the mixed-layer chlorite-smectite was calculated using Wise's method described in Bettison and Schiffman (1988) and Bevins et al. (1991). Structural formulas and corresponding X values are presented in Table 5. Chlorite-smectite in veins is more chloritic than that replacing olivine in the host-rock of the same sample. Chlorite-smectite in the rim of olivine is more chloritic than that replacing the core. Chlorite replacing clinopyroxene is not very common or abundant. It contains significant amounts of Cr$_2$O$_3$ (up to 2.7 wt%), reflecting the influence of the precursor mineral composition.

Variation of chlorite composition with depth (Fig. 8) shows zones of variable iron enrichment. The depth intervals with particularly low FeO$_t$ concentrations (i.e., 1700–1820, 1905–1938, and 1980–1985 mbsf) correspond to the occurrence of fresh olivine relicts and/or with the replacement of olivine by talc, and are negatively correlated with the calculated proportion of chlorite in phyllosilicates (X value). The zones where phyllosilicates are Mg-rich and Fe-poor (occurrence of talc and low-Fe chlorite) are thought to have been altered under relatively low water/rock ratios.

Variations of MnO with depth approximately parallel those of FeO, with a clear MnO enrichment between 1820 and 1910 m.

Considering the entire dike section (Fig. 8), the iron content of chlorite and chlorite-smectite is low in the stockwork zone, increases with depth down to 1560 mbsf (end of Leg 111), and generally decreases again in the deepest 400 meters, with the local low values mentioned above.

Talc

Talc is easily distinguished from other phyllosilicates in thin section because it is colorless and has much higher birefringence. It is common from 1705 to 1745 mbsf, 1760 to 1790 mbsf, 1815 to 1825 mbsf, 1910 to 1925 mbsf, and 1992 mbsf as a total or partial replacement of olivine, and is associated with magnetite and/or hematite. Olivine relics occur only in the talc-bearing samples.

Trace Al and interlayer cations plus minor Fe in Legs 137/140 talc (Table 6) suggest the presence of chlorite or mixed-layered chlorite-smectite in the talc, as in shallower dikes (Alt et al., 1986a, 1989b). The Fe/Al ratio of talc (4.5) is much greater than that for chlorite (0.9) or smectite (1.5) in Legs 137/140 rocks, however, suggesting that the talc is Fe-bearing. Attributing all the Al in the talc analyses to the presence of chlorite indicates that about 75% of the Fe in the analyses is contained in the talc. This is confirmed by HRTEM observation of chlorite layers in talc: pure talc layers have been analyzed by HRTEM and contain 2 wt% FeO.

Talc is interpreted as reflecting a low water/rock ratio alteration process, which can occur at temperatures from 250°C to 500°–600°C (Shipboard Scientific Party, 1992b).

Serpentine

Serpentine was tentatively identified optically during Leg 140 as a partial replacement of olivine, typically forming a band located between a talc rim and the fresh olivine core. No serpentine was found during subsequent onshore microprobe studies, but lizardite and chrysotile replacing olivine were observed with HRTEM.

Epidote

Epidote occurs sporadically in veins, vugs, and as small patches replacing plagioclase. Epidote does not coexist with relict fresh olivine, and has been found in only two talc-bearing samples. Epidote generally forms in veins from evolved fluids, so the lack of epidote in the rocks containing relict olivine and talc may be attributed to the low permeability of the crust where these rocks occur. Epidote commonly coexists with anhydrite, except in the deeper 80 m, where epidote occurs without anhydrite.

The range of composition of epidote from Legs 137/140 (Table 7) is the same as in Leg 83 (Alt et al., 1986a; Laverne, 1987b) and Leg

Table 2. Representative amphibole analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Expandable depth	Analysis	Occurrence	Mineral	SiO$_2$	Al$_2$O$_3$	FeO$_t$	MnO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	Cr$_2$O$_3$	ZnO	Cl
173R-1, 8–10	1570.4	AA17	ground.	Cumm	50.39	1.78	22.15	0.67	13.43	6.76	0.25	0.01	0.14	0.00	0.00	0.05
173R-1, 77–79	1573.1	B2184	interst./cpx	Fe-Act	52.02	2.20	20.90	0.44	10.12	12.35	0.17	0.03	0.06	0.00	0.28	0.05
176R-1, 15–17	1596.4	A1	vein	Act	52.70	1.27	20.87	0.38	11.61	10.71	0.09	0.01	0.06	0.00	0.00	0.00
	1596.4	A17	vein	Fe-Act	52.60	1.23	21.11	0.34	11.26	10.72	0.06	0.01	0.07	0.00	0.00	0.02
	1596.4	A9	vein	Mg-Hbl	46.06	11.00	18.46	0.31	12.14	8.23	1.54	0.00	0.15	0.00	0.00	0.03
	1596.4	A13	halo	Act	51.88	3.37	16.76	0.35	14.59	9.78	0.29	0.00	0.47	0.00	0.00	0.01
177R-1, 11–15	1606.2	B2108	vein	Act	52.51	2.56	17.91	0.27	13.59	10.61	0.30	0.00	0.24	0.00	0.00	0.03
186R-1, 21–23	1627.1	V4090	vein	Act	52.21	2.41	19.65	0.43	11.47	11.64	0.31	0.00	0.11	0.01	0.00	0.03
	1627.1	V4095	vein wall	Act	52.45	2.58	16.94	0.29	14.22	11.02	0.31	0.00	0.23	0.60	0.00	0.08
186R-1, 57–60	1628.1	V4100	vein	Act-Hbl	50.71	5.57	14.95	0.28	14.26	11.87	0.90	0.02	0.20	0.00	0.00	0.11
	1628.1	V4102	vein	Mg-Hbl	48.01	6.73	14.77	0.25	12.76	11.67	0.82	0.02	0.27	0.01	0.11	0.16
	1628.1	V4107	vein	Act	51.98	1.91	20.61	0.34	11.00	10.89	0.26	0.00	0.07	0.02	0.07	0.07
186R-1, 140–143	1630.1	B3107	vein	Act	52.74	3.44	13.14	0.18	16.11	10.61	0.50	0.00	0.54	0.08	0.00	0.13
186R-2, 25–28	1631.4	A29	halo	Act-Hbl	51.86	3.27	13.01	0.27	16.27	10.97	0.49	0.00	0.35	0.00	0.00	0.02
	1631.4	A32	vein	Act-Hbl	51.40	4.11	13.58	0.34	15.30	11.43	0.57	0.02	0.78	0.00	0.00	0.02
	1631.4	A33	vein	Mg-Hbl	48.85	6.46	15.07	0.23	13.23	11.38	1.14	0.02	0.39	0.00	0.00	0.02
189R-1, 105–106	1652.9	B2001	vein	Act	53.15	1.93	15.23	0.19	14.52	11.41	0.48	0.01	0.35	0.00	0.02	0.03
	1652.9	B2014	halo	Fe-Act	51.44	2.47	20.49	0.50	10.79	11.04	0.28	0.01	0.31	0.00	0.00	0.04
	1652.9	B2015	halo	Cumm	49.66	3.30	25.87	0.70	9.53	8.10	0.44	0.05	0.39	0.05	0.02	0.09
189R-1, 106–110	1653.0	V5131	vein	Act	52.96	2.06	16.25	0.29	14.17	11.19	0.32	0.00	0.32	0.01	0.00	0.05
	1653.0	V5132	vein	Act	51.72	3.74	16.10	0.34	13.96	10.82	0.49	0.02	0.28	0.06	0.03	0.06
	1653.0	V5144	vein	Fe-Act	51.59	1.28	26.81	0.61	7.89	10.12	0.21	0.03	0.12	0.02	0.09	0.11
189R-2, 76–79	1654.3	B2157	vein	Act	51.22	2.41	18.74	0.12	11.35	11.43	0.50	0.13	0.21	0.09	0.00	0.16
	1654.3	B2173	ground.	Fe-Act	50.73	1.76	26.63	0.46	7.08	11.26	0.29	0.05	0.09	0.05	0.00	0.23
189R-2, 100–104	1655.0	A45	patch	Act-Hbl	50.54	3.98	16.01	0.22	12.73	11.80	0.30	0.01	0.47	0.00	0.00	0.01
191R-1, 145–148	1670.5	B3060	ground.	Fe-Act	48.33	3.87	26.18	0.35	7.92	8.67	0.69	0.04	0.39	0.14	0.00	0.28
	1670.5	B3061	ground.	Fe-Act-Hbl	47.84	3.95	25.73	0.22	7.65	9.71	0.81	0.16	0.43	0.03	0.00	0.48
194R-1, 59–61	1684.6	A56	patch	Act-Hbl	50.77	0.54	14.79	0.47	12.12	19.22	0.29	0.00	0.16	0.00	0.00	0.00
	1684.6	A58	patch	Act	51.09	2.58	18.89	0.31	11.46	11.82	0.25	0.02	0.08	0.00	0.00	0.00
196R-1, 29–33	1700.5	B3079	vein	Act	51.83	3.38	18.04	0.45	12.48	10.72	0.36	0.05	0.24	0.11	0.00	0.06
197R-1, 44–46	1704.9	B3070	ground.	Act-Hbl	51.29	4.49	17.28	0.33	13.27	10.72	0.57	0.07	0.20	0.15	0.00	0.03
197R-1, 100–102	1708.3	A57	vein wall	Act-Hbl	50.81	4.39	14.88	0.40	13.25	11.17	0.71	0.03	0.34	0.00	0.00	0.09
	1708.3	A60	vein	Act	51.81	2.63	17.50	0.21	12.63	11.42	0.24	0.02	0.18	0.00	0.00	0.01
199R-1, 14–16	1720.4	B2135	ground.	Act-Hbl	51.74	3.59	15.92	0.27	14.65	11.93	0.75	0.09	0.04	0.08	0.00	0.08
200R-2, 18–24	1731.7	V3058	ground.	Act	51.09	3.11	19.53	0.55	13.22	9.00	0.69	0.00	0.22	0.01	0.00	0.07
	1731.7	V3062	vein	Act-Hbl	49.82	5.31	16.99	0.47	13.37	10.66	0.99	0.01	0.09	0.00	0.04	0.00
	1731.7	V3064	vein	Cumm	53.30	1.97	19.02	0.75	17.12	4.16	0.46	0.02	0.20	0.14	0.00	0.05
	1731.7	V3066	vein	Cumm	52.23	3.25	16.92	0.53	16.92	5.56	0.68	0.01	0.10	0.01	0.01	0.06
200R-2, 101–104	1733.4	B2101	vein	Act	52.32	3.30	16.60	0.51	14.56	9.48	0.57	0.02	0.21	0.03	0.00	0.01
200R-3, 108–112	1736.0	V6176	vein	Act	51.06	1.37	14.63	0.68	12.26	12.93	0.32	0.02	0.20	0.01	0.00	0.02
201R-1, 0–4	1739.3	B3132	ground.	Mg-Hbl	50.29	5.87	13.27	0.25	14.63	11.97	0.83	0.01	0.38	0.82	0.07	0.03
203R-1, 9–10	1750.9	B3021	vein	Act-Hbl	52.27	4.63	14.25	0.19	14.90	11.73	0.59	0.02	0.44	0.00	0.04	0.07
203R-1, 33–36	1753.9	V2045	ground.	Act-Hbl	50.25	5.03	13.94	0.18	14.15	10.29	0.93	0.06	0.59	0.00	0.00	0.08
	1753.9	V2033	vein	Act	53.29	2.66	16.41	0.33	14.66	10.34	0.39	0.02	0.31	0.00	0.03	0.04
	1753.9	V2037	vein	Act-Hbl	49.12	4.64	16.38	0.33	12.74	9.61	0.87	0.02	0.27	0.04	0.06	0.19
	1753.9	V2039	shear zone	Act	52.73	3.11	15.57	0.23	14.34	11.21	0.43	0.00	0.27	0.01	0.00	0.06
204R-1, 11–14	1756.6	V5165	vein	Act-Hbl	51.07	3.00	17.65	0.42	14.56	9.78	0.64	0.00	0.28	0.08	0.02	0.04
	1756.6	V5166	vein	Act	53.28	1.68	15.34	0.36	15.98	10.52	0.27	0.02	0.16	0.00	0.04	0.04
	1756.6	V5169	ground.	Act-Hbl	50.49	3.35	14.55	0.22	14.05	12.22	0.40	0.00	0.52	0.21	0.15	0.02
205R-1, 13–16	1757.4	A62	vein	Mg-Hbl	47.69	7.52	14.96	0.22	14.74	11.05	1.54	0.12	0.64	0.00	0.00	0.05
	1757.4	A70	halo	Mg-Hbl	50.72	4.81	13.87	0.31	14.01	11.59	0.64	0.03	0.50	0.00	0.00	0.03
208R-1, 88–91	1776.2	A70	halo	Mg-Hbl	48.02	4.45	19.50	0.36	12.01	10.43	0.52	0.02	0.19	0.00	0.00	0.05
208R-3, 1–4	1787.5	A73	halo	Act-Hbl	50.72	4.81	13.87	0.31	14.01	11.59	0.64	0.03	0.50	0.00	0.00	0.01
	1787.5	A75	halo	Mg-Hbl	49.55	12.40	8.27	0.17	8.99	16.59	0.33	0.00	0.21	0.00	0.00	0.00
209R-2, 146–149	1794.7	V6182	halo	Act-Hbl	50.80	4.05	15.65	0.27	13.22	11.25	0.50	0.03	0.24	0.11	0.03	0.07
	1794.7	V6183	plag. crack	Act	51.16	4.06	16.11	0.26	13.16	10.74	0.54	0.02	0.25	0.04	0.00	0.03
210R-1, 56–60	1795.9	B3116	vein	Act	53.11	2.40	17.78	0.11	12.04	12.23	0.31	0.01	0.16	0.04	0.21	0.00
213R-1, 3–6	1812.8	V1025	vein	Mg-Hbl	49.05	5.86	14.94	0.18	14.04	12.19	1.31	0.11	1.94	0.00	0.11	0.36
	1812.8	V1027	vein	Act	52.88	2.04	18.21	0.44	12.09	11.45	0.25	0.00	0.11	0.06	0.06	0.04
	1812.8	V1028	ground.	Act-Hbl	51.78	3.98	16.74	0.38	13.02	11.16	0.57	0.01	0.21	0.36	0.00	0.00
213R-1, 45–47	1814.9	P67	patch	Act-Hbl	50.07	4.72	11.69	0.13	15.33	11.52	0.64	0.02	0.16	0.10	nd	0.02
214R-1, 28–30	1819.0	B2140	patch	Act-Hbl	50.75	5.94	15.66	0.26	13.35	11.90	0.89	0.02	0.40	0.00	0.00	0.11
	1819.0	B2149	vein	Edenite	47.01	6.39	12.74	0.07	12.74	10.33	1.74	0.07	1.30	0.00	0.00	0.06
	1819.0	B2150	vein	Mg-Hbl	51.18	5.06	13.67	0.12	15.44	11.10	1.19	0.16	0.68	0.13	0.16	0.27
	1819.0	B2153	vein	Act-Hbl	50.88	5.56	14.89	0.26	14.14	11.55	0.81	0.04	0.52	0.19	0.16	0.05
214R-1, 67–70	1819.5	B2187	vein	Mg-Hbl	48.02	6.91	13.87	0.27	14.70	11.05	1.23	0.06	1.02	0.00	0.00	0.23
	1819.5	B2198	vein	Edenite	48.83	6.68	14.08	0.32	15.46	10.87	2.02	0.06	0.09	0.11	0.00	0.36
214R-1, 76–78	1819.6	P2	ground.	Act-Hbl	50.44	3.68	13.09	0.18	16.11	10.54	0.74	0.04	0.44	0.06	nd	0.07
	1819.6	P15	ground.	Edenite	47.16	7.89	13.12	0.15	15.57	10.51	2.09	0.05	0.40	0.00	nd	0.20
	1819.6	P17	ground.	Act	52.07	2.00	17.66	0.39	14.67	9.48	0.54	0.06	0.36	0.04	nd	0.10
214R-2, 0–5	1820.9	B3123	vein	Act	53.59	1.48	18.44	0.30	13.21	11.39	0.36	0.02	0.25	0.02	0.00	0.15
	1820.9	B3126	vein	Act	53.64	2.35	15.73	0.16	14.44	10.81	0.50	0.00	0.32	0.00	0.00	0.10
214R-2, 29–32	1821.4	P24	ground.	Mg-Hbl	46.55	5.87	19.78	0.18	11.30	10.02	1.10	0.06	0.15	0.04	nd	0.17
223R-1, 9–11	1896.8	B3023	vein	Act	51.66	3.82	15.27	0.19	13.78	12.08	0.56	0.04	0.17	0.03	0.00	0.05
	1896.8	B3025	halo	Act-Hbl	50.12	4.55	15.69	0.25	13.31	11.45	0.88	0.01	0.68	0.10	0.00	0.06
	1896.8	B3030	ground.	Mg-Hbl	49.05	6.92	15.94	0.40	13.86	10.19	0.75	0.01	0.48	0.00	0.00	0.08
225R-1, 91–93	1915.2	A96	halo	Act-Hbl	51.05	4.78	14.02	0.38	15.00	9.97	0.77	0.02	0.25	0.00	0.00	0.02
	1915.2	A100	vein	Mg-Hbl	49.20	5.73	14.15	0.07	13.54	11.48	0.96	0.07	0.47	0.00	0.00	0.16
225R-2, 68–70	1919.5	AA127	vein	Act-Hbl	49.98	2.94	15.22	0.20	14.59	11.80	0.38	0.01	0.17	0.00	0.00	0.04
	1919.5	AA129	halo	Mg-Hbl	45.41	7.40	14.78	0.19	13.39	11.94	1.26	0.05	0.49	0.00	0.00	0.09
	1919.5	AA133	host	Fe-Hbl	45.76	3.71	26.34	0.28	7.99	9.55	0.85	0.25	0.65	0.00	0.00	0.42
226R-1, 99–102	1921.4	B2073	ground.	Act-Hbl	50.46	4.57	15.67	0.36	14.03	11.90	0.74	0.04	0.37	0.00	0.00	0.06
	1921.4	B2074	ground.	Act	52.25	3.51	17.25	0.36	14.16	10.61	0.53	0.06	0.15	0.00	0.00	0.00
226R-3, 5–9	1924.0	B2083	ground.	Act	51.68	2.75	19.50	0.56	13.50	8.86	0.60	0.00	0.41	0.00	0.01	0.06
	1924.0	B2084	ground.	Act-Hbl	50.06	5.07	15.52	0.20	13.81	11.36	0.76	0.00	0.30	0.00	0.00	0.11
	1924.0	B2085	ground.	Mg-Hbl	48.91	6.80	16.72	0.38	13.65	9.94	1.30	0.03	0.33	0.01	0.04	0.06
230R-1, 14–17	1953.5	B3035	vein	Act	52.95	2.72	16.67	0.23	14.13	10.68	0.45	0.03	0.17	0.00	0.00	0.09
	1953.5	B3037	halo	Mg-Hbl	50.10	5.18	15.81	0.16	13.69	10.96	0.93	0.08	1.01	0.21	0.00	0.34
	1953.5	B3038	halo	Act-Hbl	50.83	4.39	15.69	0.28	14.13	10.33	0.88	0.09	0.76	0.08	0.07	0.19
	1953.5	B3040	ground.	Mg-Hbl	48.69	7.20	16.68	0.40	12.52	10.89	1.14	0.06	0.23	0.00	0.00	0.06
235R-1, 8–10	1977.4	A1	vein	Act-Hbl	51.44	4.21	15.16	0.27	13.66	11.50	0.55	0.02	0.37	0.01	0.11	0.09
	1977.4	A5	vein	Act	50.81	3.54	15.80	0.25	12.72	12.01	0.45	0.01	0.28	0.00	0.04	0.11
	1977.4	A11	halo	Mg-Hbl	49.37	5.87	15.40	0.26	12.77	11.48	0.79	0.04	0.46	0.00	0.00	0.04

111 (Ishizuka, 1989) rocks. Ishizuka (1989) found evidence of two populations of epidote XFe^{3+} values (= $Fe^{3+}/Al + Fe^{3+}$) in Leg 111 rocks: XFe^{3+} ranges from 0.16 to 2.2 in epidotes coexisting with prehnite and actinolite, whereas XFe^{3+} ranges from 2.4 to 2.9 in epidotes coexisting with prehnite and laumontite. XFe^{3+} ranges from 0.16 to 0.32, with a mode at 0.26, in epidotes from Legs 137/140 section.

Prehnite

Prehnite is widespread in Legs 137/140 dolerites, although it is not important volumetrically. It occurs in interstitial areas or small vugs, together with epidote, laumontite, actinolite and chlorite. In most cases, chlorite rims the amygdules and obviously formed prior to

Table 2 (continued).

Total	Si	Al^{IV}	Al^{VI}	Ti	Cr	Fe^{2+}	Fe^{3+}	Mn	Mg	MgM4	Ca	NaM4	NaA	K	Total	XMg	(Na+K)A
95.99	7.602	0.317	0.000	0.016	0.000	2.276	0.519	0.086	3.019	0.000	1.093	0.073	0.000	0.002	15.002	0.57	0.002
98.57	7.739	0.261	0.125	0.007	0.000	2.533	0.068	0.055	2.213	0.031	1.969	0.000	0.049	0.006	15.077	0.47	0.055
97.70	7.829	0.171	0.051	0.007	0.000	2.462	0.130	0.048	2.570	0.000	1.705	0.026	0.000	0.002	15.002	0.51	0.002
97.42	7.856	0.144	0.073	0.008	0.000	2.566	0.071	0.043	2.506	0.000	1.716	0.017	0.000	0.002	15.002	0.49	0.002
97.95	6.598	1.402	0.452	0.016	0.000	0.866	1.345	0.038	2.592	0.000	1.263	0.428	0.000	0.000	15.000	0.75	0.000
97.52	7.533	0.467	0.110	0.051	0.000	1.699	0.366	0.043	3.157	0.000	1.522	0.082	0.000	0.000	15.000	0.65	0.000
98.02	7.682	0.318	0.123	0.026	0.000	2.133	0.058	0.033	2.626	0.337	1.663	0.000	0.085	0.000	15.104	0.58	0.085
98.27	7.715	0.285	0.135	0.012	0.001	2.393	0.035	0.054	2.369	0.157	1.843	0.000	0.089	0.000	15.100	0.51	0.089
98.72	7.598	0.402	0.038	0.025	0.069	1.894	0.158	0.036	2.780	0.290	1.710	0.000	0.087	0.000	15.139	0.62	0.087
98.87	7.304	0.696	0.250	0.022	0.000	1.653	0.147	0.034	2.893	0.168	1.832	0.000	0.251	0.004	15.304	0.65	0.255
95.58	7.184	0.816	0.371	0.030	0.001	1.708	0.141	0.032	2.717	0.129	1.871	0.000	0.238	0.004	15.288	0.62	0.242
97.22	7.767	0.233	0.103	0.008	0.002	2.388	0.188	0.043	2.268	0.181	1.743	0.075	0.000	0.000	15.061	0.51	0.000
97.47	7.552	0.448	0.132	0.058	0.009	1.245	0.329	0.022	3.205	0.233	1.628	0.139	0.000	0.000	15.108	0.73	0.000
96.54	7.477	0.523	0.033	0.038	0.000	1.017	0.551	0.033	3.496	0.000	1.695	0.137	0.000	0.000	15.000	0.77	0.000
97.62	7.369	0.631	0.063	0.084	0.000	1.074	0.555	0.041	3.269	0.000	1.756	0.158	0.000	0.004	15.004	0.75	0.004
96.86	7.067	0.933	0.170	0.042	0.000	0.829	0.994	0.028	2.853	0.000	1.764	0.320	0.000	0.004	15.004	0.77	0.004
97.32	7.712	0.288	0.042	0.038	0.000	1.544	0.304	0.023	3.049	0.091	1.774	0.135	0.000	0.001	15.101	0.67	0.001
97.37	7.712	0.288	0.148	0.035	0.000	2.569	0.000	0.063	2.184	0.227	1.773	0.000	0.081	0.002	15.079	0.48	0.083
98.20	7.525	0.475	0.114	0.044	0.006	3.151	0.127	0.090	1.467	0.685	1.315	0.000	0.129	0.010	15.181	0.41	0.139
97.62	7.744	0.256	0.099	0.035	0.001	1.987	0.000	0.036	2.841	0.247	1.753	0.000	0.091	0.000	15.089	0.61	0.091
97.62	7.566	0.434	0.211	0.031	0.007	1.958	0.012	0.042	2.740	0.304	1.696	0.000	0.139	0.004	15.147	0.61	0.143
98.88	7.837	0.163	0.066	0.014	0.002	3.406	0.000	0.078	1.434	0.353	1.647	0.000	0.062	0.006	15.068	0.34	0.068
96.36	7.668	0.332	0.093	0.024	0.011	2.045	0.301	0.015	2.511	0.022	1.833	0.145	0.000	0.025	15.124	0.55	0.025
98.63	7.750	0.250	0.067	0.010	0.006	3.341	0.061	0.060	1.455	0.157	1.843	0.000	0.086	0.010	15.116	0.33	0.096
96.08	7.479	0.521	0.174	0.052	0.000	1.655	0.326	0.028	2.808	0.000	1.871	0.086	0.000	0.002	15.002	0.63	0.002
96.86	7.404	0.596	0.102	0.045	0.017	2.770	0.584	0.045	1.436	0.372	1.423	0.205	0.000	0.008	15.201	0.40	0.008
97.01	7.448	0.552	0.172	0.050	0.004	3.350	0.000	0.029	1.395	0.380	1.620	0.000	0.244	0.032	15.276	0.35	0.276
98.37	7.357	0.092	0.000	0.017	0.000	0.552	1.241	0.058	2.617	0.000	2.985	0.081	0.000	0.000	15.000	0.83	0.000
96.50	7.627	0.373	0.081	0.009	0.000	2.015	0.343	0.039	2.550	0.000	1.891	0.072	0.000	0.004	15.004	0.56	0.004
97.72	7.597	0.403	0.181	0.026	0.013	1.962	0.249	0.056	2.512	0.214	1.684	0.102	0.000	0.009	15.091	0.58	0.009
98.40	7.481	0.519	0.252	0.022	0.017	2.076	0.032	0.041	2.560	0.325	1.675	0.000	0.161	0.013	15.185	0.58	0.174
96.07	7.462	0.538	0.223	0.038	0.000	1.392	0.435	0.011	2.901	0.000	1.759	0.203	0.000	0.006	14.968	0.68	0.006
96.69	7.665	0.335	0.124	0.020	0.000	1.929	0.236	0.026	2.785	0.000	1.810	0.069	0.000	0.004	15.004	0.59	0.004
99.14	7.446	0.554	0.055	0.004	0.009	1.661	0.255	0.033	2.982	0.160	1.840	0.000	0.209	0.017	15.311	0.65	0.226
97.49	7.582	0.418	0.126	0.025	0.001	2.381	0.043	0.069	2.355	0.569	1.431	0.000	0.199	0.000	15.213	0.55	0.199
97.75	7.319	0.681	0.239	0.010	0.000	1.949	0.139	0.058	2.606	0.322	1.678	0.000	0.282	0.002	15.330	0.60	0.284
97.19	7.740	0.260	0.077	0.022	0.016	2.062	0.248	0.092	2.482	1.223	0.647	0.130	0.000	0.004	15.085	0.64	0.004
96.47	7.616	0.384	0.174	0.011	0.001	1.686	0.377	0.065	2.685	0.697	1.111	0.192	0.000	0.002	15.126	0.67	0.002
97.61	7.570	0.430	0.133	0.023	0.003	1.605	0.404	0.063	2.770	0.370	1.470	0.160	0.000	0.004	15.137	0.66	0.004
93.50	7.782	0.218	0.029	0.023	0.001	1.644	0.231	0.088	2.785	0.000	1.916	0.084	0.009	0.003	15.012	0.63	0.012
98.42	7.248	0.752	0.245	0.041	0.093	1.501	0.098	0.031	2.991	0.152	1.848	0.000	0.232	0.002	15.266	0.68	0.234
99.13	7.473	0.527	0.254	0.047	0.000	1.693	0.011	0.023	2.972	0.203	1.797	0.000	0.164	0.004	15.171	0.65	0.168
95.50	7.364	0.636	0.233	0.065	0.000	1.183	0.525	0.022	2.971	0.120	1.616	0.264	0.000	0.011	15.185	0.72	0.011
98.50	7.661	0.339	0.111	0.034	0.000	1.706	0.266	0.040	2.842	0.299	1.593	0.109	0.000	0.004	15.091	0.65	0.004
94.27	7.385	0.615	0.207	0.031	0.005	1.467	0.592	0.042	2.656	0.198	1.548	0.254	0.000	0.004	15.200	0.66	0.004
97.96	7.602	0.398	0.131	0.029	0.001	1.550	0.327	0.028	2.933	0.148	1.732	0.120	0.000	0.000	15.108	0.67	0.000
97.54	7.497	0.503	0.016	0.031	0.009	1.934	0.233	0.052	2.724	0.462	1.538	0.000	0.182	0.000	15.259	0.62	0.182
97.69	7.714	0.286	0.001	0.017	0.000	1.686	0.171	0.044	3.080	0.368	1.632	0.000	0.076	0.004	15.136	0.67	0.080
96.18	7.470	0.530	0.054	0.058	0.025	1.580	0.221	0.028	3.035	0.063	1.937	0.000	0.115	0.000	15.188	0.66	0.115
98.67	6.715	1.249	0.000	0.068	0.000	0.177	1.585	0.026	3.093	0.000	1.668	0.420	0.000	0.022	15.022	0.95	0.022
96.50	7.374	0.626	0.199	0.055	0.000	1.194	0.492	0.024	3.036	0.000	1.806	0.180	0.000	0.006	15.006	0.72	0.006
95.91	7.195	0.786	0.000	0.021	0.000	1.516	0.927	0.046	2.682	0.000	1.675	0.151	0.000	0.004	15.004	0.95	0.004
96.50	7.374	0.626	0.199	0.055	0.000	1.194	0.492	0.038	3.036	0.000	1.806	0.180	0.000	0.006	15.006	0.72	0.006
96.50	7.128	0.872	1.230	0.000	0.000	0.998	0.003	0.021	1.927	0.000	2.558	0.092	0.000	0.000	15.000	0.66	0.000
96.25	7.476	0.524	0.179	0.026	0.013	1.529	0.416	0.033	2.900	0.000	1.775	0.125	0.018	0.006	15.024	0.65	0.024
96.37	7.521	0.479	0.224	0.028	0.004	1.652	0.346	0.033	2.883	0.000	1.693	0.138	0.015	0.004	15.019	0.64	0.019
98.40	7.757	0.243	0.170	0.018	0.005	2.052	0.119	0.014	2.621	0.000	1.914	0.088	0.000	0.002	15.041	0.56	0.002
100.09	7.071	0.929	0.067	0.210	0.000	1.746	0.055	0.022	2.900	0.117	1.883	0.000	0.366	0.020	15.405	0.63	0.386
97.63	7.793	0.207	0.147	0.012	0.007	2.144	0.101	0.055	2.535	0.121	1.808	0.071	0.000	0.000	15.033	0.55	0.000
98.21	7.490	0.510	0.168	0.023	0.041	1.612	0.413	0.047	2.696	0.111	1.730	0.160	0.000	0.002	15.138	0.64	0.002
94.40	7.443	0.557	0.270	0.018	0.012	1.401	0.052	0.016	3.231	0.165	1.835	0.000	0.184	0.004	15.205	0.71	0.188
99.28	7.319	0.681	0.328	0.043	0.000	1.875	0.014	0.032	2.708	0.161	1.839	0.000	0.249	0.004	15.257	0.60	0.253
95.67	6.976	1.024	0.093	0.145	0.000	1.454	0.127	0.009	3.172	0.358	1.642	0.000	0.501	0.013	15.557	0.71	0.514
99.06	7.208	0.792	0.048	0.072	0.014	0.729	0.882	0.014	3.241	0.000	1.675	0.325	0.000	0.029	15.322	0.82	0.029
99.05	7.332	0.668	0.276	0.056	0.022	1.770	0.025	0.032	2.820	0.217	1.783	0.000	0.226	0.007	15.242	0.63	0.233
97.36	7.027	0.973	0.218	0.112	0.000	1.527	0.170	0.033	2.939	0.268	1.732	0.000	0.349	0.011	15.417	0.68	0.360
98.88	7.071	0.929	0.210	0.010	0.013	1.596	0.109	0.039	3.023	0.314	1.686	0.000	0.567	0.011	15.615	0.68	0.578
95.39	7.450	0.550	0.090	0.049	0.007	1.481	0.136	0.023	3.214	0.332	1.668	0.000	0.212	0.008	15.264	0.71	0.220
97.14	6.913	1.087	0.276	0.044	0.000	1.489	0.119	0.019	3.053	0.349	1.651	0.000	0.594	0.009	15.644	0.70	0.603
97.37	7.669	0.331	0.016	0.040	0.005	2.109	0.066	0.049	2.716	0.504	1.496	0.000	0.154	0.011	15.187	0.60	0.165
99.21	7.796	0.204	0.050	0.027	0.002	2.243	0.000	0.037	2.640	0.225	1.775	0.000	0.102	0.004	15.102	0.56	0.106
98.05	7.735	0.265	0.135	0.035	0.000	1.697	0.200	0.020	2.914	0.190	1.670	0.140	0.000	0.000	15.066	0.65	0.000
95.22	7.133	0.867	0.193	0.017	0.005	2.240	0.295	0.023	2.226	0.355	1.645	0.000	0.327	0.012	15.438	0.54	0.339
97.65	7.543	0.457	0.201	0.019	0.003	1.816	0.049	0.023	2.889	0.110	1.890	0.000	0.159	0.007	15.182	0.62	0.166
97.10	7.403	0.597	0.195	0.076	0.012	1.938	0.000	0.031	2.749	0.181	1.812	0.000	0.252	0.002	15.247	0.60	0.254
97.68	7.156	0.844	0.346	0.053	0.000	1.767	0.178	0.049	2.607	0.407	1.593	0.000	0.212	0.002	15.273	0.63	0.214
96.29	7.402	0.598	0.219	0.027	0.000	1.163	0.537	0.047	3.241	0.000	1.549	0.216	0.000	0.004	15.004	0.74	0.004
95.79	7.197	0.803	0.185	0.052	0.000	0.957	0.774	0.009	2.952	0.000	1.800	0.272	0.000	0.013	15.013	0.76	0.013
95.68	7.380	0.512	0.000	0.019	0.000	1.082	0.796	0.025	3.210	0.000	1.868	0.108	0.000	0.003	15.003	0.75	0.003
95.37	6.663	1.281	0.000	0.054	0.000	0.178	1.635	0.024	2.928	0.000	1.877	0.360	0.000	0.010	15.010	0.94	0.010
95.81	7.099	0.679	0.000	0.076	0.000	2.239	1.179	0.037	1.846	0.000	1.588	0.256	0.000	0.050	15.050	0.45	0.050
98.20	7.335	0.665	0.117	0.040	0.000	1.654	0.251	0.044	2.893	0.147	1.853	0.000	0.209	0.007	15.299	0.65	0.216
98.88	7.558	0.442	0.156	0.016	0.000	1.992	0.094	0.044	2.697	0.356	1.644	0.000	0.149	0.011	15.191	0.61	0.160
97.93	7.628	0.372	0.106	0.046	0.000	2.404	0.003	0.070	2.371	0.599	1.401	0.000	0.172	0.000	15.173	0.55	0.172
97.19	7.350	0.650	0.227	0.033	0.000	1.765	0.140	0.025	2.809	0.213	1.787	0.000	0.216	0.000	15.263	0.63	0.216
98.17	7.159	0.841	0.332	0.036	0.001	1.986	0.061	0.047	2.537	0.441	1.559	0.000	0.369	0.006	15.395	0.60	0.375
98.12	7.652	0.348	0.115	0.018	0.000	1.698	0.316	0.028	2.823	0.220	1.654	0.126	0.000	0.006	15.109	0.64	0.006
98.47	7.196	0.804	0.072	0.109	0.024	1.165	0.734	0.019	2.876	0.054	1.687	0.259	0.000	0.015	15.258	0.72	0.015
97.72	7.343	0.657	0.091	0.083	0.009	1.274	0.622	0.034	2.888	0.155	1.599	0.246	0.000	0.017	15.222	0.70	0.017
97.91	7.163	0.837	0.411	0.025	0.000	2.013	0.039	0.050	2.462	0.284	1.716	0.000	0.325	0.011	15.349	0.58	0.336
97.38	7.466	0.534	0.187	0.040	0.001	1.422	0.418	0.033	2.955	0.000	1.788	0.156	0.000	0.003	15.003	0.68	0.003
96.02	7.521	0.479	0.139	0.032	0.000	1.551	0.406	0.031	2.806	0.000	1.905	0.130	0.000	0.001	15.001	0.64	0.001
96.46	7.218	0.782	0.230	0.050	0.000	1.215	0.668	0.032	2.783	0.000	1.798	0.223	0.000	0.007	15.007	0.70	0.007

other secondary minerals. Whether prehnite is in equilibrium with epidote and/or actinolite is not clear. Prehnite also occurs in later veins associated with epidote. It partly replaces plagioclase, particularly when in alteration patches.

Some representative analyses of prehnite from Legs 137/140 are presented in Table 8. Compositions are similar to those of Leg 111

prehnites coexisting with epidote and laumontite reported by Ishizuka (1989), although their XFe^{3+} ratio can still be lower. Leg 83 prehnites also generally have lower XFe^{3+} than Leg 111 ones. This difference may be because the prehnite we analyzed in Legs 137/140 rocks is not associated with either epidote, laumontite, or actinolite, as it is in Leg 111 rocks. This relatively low XFe^{3+} suggests that prehnite from Legs

Table 2 (continued).

Core, section, interval (cm)	Expandable depth	Analysis	Occurrence	Mineral	SiO₂	Al₂O₃	FeOₜ	MnO	MgO	CaO	Na₂O	K₂O	TiO₂	Cr₂O₃	ZnO	Cl
236R-1, 5–9	1977.4	A16	ground.	Act	52.23	3.09	18.15	0.38	12.78	11.10	0.39	0.02	0.22	0.00	0.08	0.05
	1981.0	A27	vein wall	Fe-Act	51.85	0.85	24.59	0.48	8.14	9.50	0.62	0.00	0.26	0.02	0.00	0.05
	1981.0	A28	vein wall	Act	51.69	3.49	16.37	0.27	12.03	12.26	0.40	0.00	0.27	0.03	0.00	0.05
	1981.0	A30	ground.	Act-Hbl	51.71	4.86	13.17	0.22	14.74	10.62	0.68	0.02	0.32	0.01	0.06	0.06
	1981.0	A38	vein	Act-Hbl	50.35	3.90	17.19	0.28	12.51	12.15	0.47	0.03	0.29	0.02	0.07	0.03
	1981.0	A46	vein	Act	51.56	2.86	15.82	0.25	13.37	11.54	0.48	0.00	0.14	0.05	0.00	0.15
236R-1, 30–32	1981.8	B3135	vein	Act	52.94	2.80	16.44	0.19	13.78	11.62	0.34	0.02	0.27	0.11	0.15	0.00
236R-1, 57–60	1982.5	B3084	vein	Act-Hbl	50.84	5.51	14.61	0.10	14.40	11.22	0.80	0.06	0.39	0.06	0.28	0.05
	1982.5	B3085	ground.	Act-Hbl	48.78	3.69	14.13	0.29	14.47	8.69	0.63	0.05	0.18	0.39	0.09	0.25
236R-1, 67–68	1982.8	V1005	vein	Edenite	46.07	8.15	15.40	0.13	13.65	11.08	2.35	0.07	0.28	0.00	0.05	0.13
	1982.8	V1008	vein	Fe-Act	52.61	0.82	15.80	0.26	7.43	11.00	0.31	0.00	0.06	0.00	0.00	0.05
	1982.8	V1014	vein	Act	54.60	2.06	14.55	0.27	15.99	9.81	1.12	0.03	0.23	0.00	0.14	0.03
	1982.8	V1016	vein wall	Act-Hbl	51.64	4.23	15.80	0.28	13.55	11.41	0.67	0.03	0.28	0.01	0.02	0.05
	1982.8	V1017	vein wall	Act	52.87	3.79	15.91	0.36	14.33	10.98	0.66	0.02	0.19	0.06	0.00	0.11
237R-1, 24–26	1991.1	B3003	vein	Act	54.19	1.73	16.58	0.31	13.80	11.68	0.24	0.00	0.16	0.09	0.00	0.06
	1991.1	A102	halo	Act	53.17	3.17	12.53	0.11	16.17	11.86	0.48	0.03	0.09	0.00	0.00	0.00
	1991.1	A103	halo	Act-Hbl	51.07	5.56	12.92	0.23	14.71	11.45	0.77	0.00	0.32	0.00	0.00	0.01

Figure 7. Molar compositions of Legs 137/140 chlorites and mixed-layer chlorite-smectites. Fields of chlorites and mixed-layer clays from Leg 83 and Leg 111 rocks are shown for comparison (Alt et al., 1985, 1989b; Laverne, 1987b).

137/140 formed at higher T or lower oxygen fugacity than that of Leg 111.

Zeolites

Zeolites are minor phases in Leg 137/140 rocks. Zeolites occur in the central part of some actinolitic veins, frequently with epidote and/or very thin amphibole needles and/or prehnite, inside tension gashes opened within actinolite crystals filling the veins in Core 186 (Tartarotti et al., this volume), as a late phase in amygdules, and as partial replacement of either fresh or previously altered plagioclase. Different zeolites could not be distinguished optically, but different compositions (laumontite and heulandite [or stilbite?]) were identified by microprobe analyses (Table 9). Both of these zeolites occur in all of the above sites.

Titanite

Titanite is common in alteration halos around veins and in alteration patches. It occurs as anhedral to euhedral, sometimes granular,

FeOt

Figure 8. Plot of total FeO vs. depth for chlorite and mixed-layer chlorite-smectite for the complete sheeted dikes section of Hole 504B. Note that low Fe contents correspond to depth zones where fresh olivine relicts (bold line) occur.

crystals partly or completely replacing titanomagnetite. Its composition is fairly constant (Table 10), and is in the range of composition of Leg 83 and Leg 111 titanite (Fig. 9). Most of Hole 504B titanite analyses plot in the composition field of greenschist to amphibolite facies rocks from East Taiwan ophiolites (Liou and Ernst, 1979).

Anhydrite

Anhydrite occurs as a partial replacement of plagioclase in some highly altered patches, and in veins where quartz, epidote, prehnite, and laumontite also occur. Anhydrite apparently formed later than the other minerals but, as for the other minerals, the presence of anhydrite reflects the high permeability of these rocks, even after the crystallization of the first stage alteration minerals.

Apatite

Secondary apatite is a common accessory mineral that forms fine acicular crystals within actinolite veins, and within the interstitial actinolite occurring in vein halos. Secondary apatite has also been identified in amphibole replacing rims of clinopyroxene in Leg 111 dike samples (J. Alt, unpubl. data).

Table 2 (continued).

Total	Si	Al^{IV}	Al^{VI}	Ti	Cr	Fe^{2+}	Fe^{3+}	Mn	Mg	MgM4	Ca	NaM4	NaA	K	Total	XMg	(Na+K)A
98.48	7.589	0.411	0.118	0.023	0.000	2.207	0.015	0.000	2.788	0.000	1.741	0.000	0.111	0.004	15.115	0.60	0.115
96.37	7.972	0.028	0.126	0.030	0.002	3.138	0.025	0.063	1.866	0.000	1.566	0.185	0.000	0.000	15.000	0.37	0.000
96.87	7.615	0.385	0.222	0.030	0.004	1.805	0.212	0.034	2.642	0.000	1.936	0.114	0.000	0.000	15.000	0.59	0.000
96.47	7.490	0.510	0.320	0.035	0.001	1.289	0.307	0.027	3.182	0.000	1.648	0.191	0.000	0.004	15.004	0.71	0.004
97.29	7.377	0.623	0.052	0.032	0.002	1.473	0.634	0.035	2.732	0.000	1.907	0.134	0.000	0.006	15.006	0.65	0.006
96.21	7.601	0.399	0.099	0.016	0.006	1.550	0.401	0.031	2.937	0.000	1.823	0.138	0.000	0.000	15.000	0.65	0.000
98.66	7.678	0.322	0.156	0.029	0.013	1.994	0.000	0.023	2.784	0.194	1.806	0.000	0.096	0.004	15.098	0.60	0.100
98.32	7.371	0.629	0.312	0.043	0.007	1.771	0.000	0.012	2.855	0.257	1.743	0.000	0.225	0.011	15.232	0.64	0.236
91.64	7.487	0.513	0.154	0.021	0.047	1.365	0.448	0.038	2.927	0.384	1.429	0.187	0.000	0.010	15.157	0.71	0.010
97.36	6.836	1.164	0.261	0.031	0.000	1.760	0.151	0.016	2.780	0.239	1.761	0.000	0.676	0.013	15.741	0.63	0.689
100.17	7.859	0.141	0.004	0.007	0.000	3.239	0.213	0.033	1.505	0.150	1.761	0.090	0.000	0.000	15.070	0.34	0.000
98.83	7.718	0.282	0.061	0.024	0.000	1.247	0.473	0.032	3.162	0.207	1.486	0.307	0.000	0.005	15.161	0.73	0.005
97.97	7.447	0.553	0.166	0.030	0.001	1.399	0.507	0.034	2.863	0.050	1.763	0.187	0.000	0.006	15.173	0.68	0.006
99.28	7.514	0.486	0.149	0.020	0.007	1.423	0.468	0.043	2.890	0.146	1.672	0.182	0.000	0.004	15.158	0.68	0.004
98.84	7.809	0.191	0.102	0.017	0.010	1.887	0.111	0.038	2.834	0.130	1.803	0.067	0.000	0.000	15.036	0.61	0.000
97.63	7.575	0.425	0.108	0.010	0.000	1.068	0.425	0.013	3.433	0.000	1.810	0.133	0.000	0.005	15.005	0.76	0.005
97.06	7.327	0.673	0.268	0.035	0.000	1.000	0.551	0.028	3.145	0.000	1.760	0.214	0.000	0.000	15.000	0.76	0.000

Notes: interst/cpx = interstitial or replacing clinopyroxene; ground = groundmass; plag crack = filling crack in plagioclase.

Table 3. Distribution (%) of amphibole compositions from different textural sites in Hole 504B dolerites, Legs 137/140.

	Actinolite	Fe-Actinolite	Act-Hornblende	Mg-Hornblende	Edenite	Cumming-tonite
Vein	55	4.3	19	11	4.3	
Vein walls	54	7.6	23	15		4.3
Halo	19	9	34	35		
Groundmass (out of halo)	36	5	29	15	12	

GEOTHERMOMETRY

Pyroxene

The equilibrium crystallization temperature of hydrothermal clinopyroxene is constrained by the experimentally determined two-pyroxene solvus (Lindsley, 1983; Lindsley and Anderson, 1983). These temperatures are strictly valid only when two pyroxenes coexist in equilibrium. Assuming that hydrothermal clinopyroxene grew in equilibrium with fluid and that there was no kinetic barrier to nucleating orthopyroxene if it was stable, the solvus temperature for a given clinopyroxene projected into the pyroxene quadrilateral (Lindsley and Anderson, 1983) represents a minimum equilibrium temperature. Thus, a composition that plots on the 500°C isotherm may have crystallized at higher temperature, but if it crystallized be-low 500°C the stable pyroxene would have been more calcic. The uncertainty in the solvus temperatures is about ±20°–110°C (typically ±70°C) for the hydrothermal pyroxenes from Hole 504B, which contain 2–18 mol% (typically 10%) non-quadrilateral components (uncertainty increases by about ±5°C or each mol% of non-quadrilateral components exceeding 2 mol%, according to Lindsley [1983]).

The temperatures of formation determined for the Na, Ti-rich pyroxenes from Samples 137-504B-177R-1, 11–15 cm (Piece 4A) and 137-504B-180M-1, 74–78 cm (Piece 7), from 1606.2 to 1619.7 mbsf range from less than 500° to 600°C (Fig. 10). The colorless secondary pyroxene (Samples 137-504B-173R-1, 77–79 cm (Piece 9), 140-504B-189R-2, 100–104 cm (Piece 14), and 140-504B-213R-1, 24–26 cm (Piece 7), from 1573.1 to 1812.8 mbsf) suggests minimum temperatures of equilibration ranging from 500°C to as high as about 700°C (Fig. 10). These temperatures are similar to those determined for secondary clinopyroxenes, some bearing aqueous fluid inclusions, from altered gabbros of Hole 735B in the Southwest Indian Ridge (Stakes et al., 1991; Vanko and Stakes, 1991).

The origin of the fluids associated with these secondary clinopyroxene is uncertain. Na and/or Ti and/or Al-rich secondary augite has been reported previously from Hole 504B. It occurs sporadically in massive flows of the Upper Pillow Alteration Zone (in two samples at 572 mbsf depth: one in which Ti, Na-rich augite is associated with melanite, a Ti-rich garnet, and one containing aegirine augite

Figure 9. Al-Ti-Fe diagram for titanite from Hole 504B. Crosses: Legs 83/111; open circles: Legs 137/140. Reference composition fields are: 1 = prehnite-pumpellyite facies, Central Sweden (Nyström, 1983); 2 = pumpellyite-actinolite facies, Central Sweden (Nyström, 1983); 3 = greenschist to amphibolite facies, East Taiwan ophiolite (Liou and Ernst, 1979).

Figure 10. Clinopyroxene compositions, recalculated following the algorithm of Lindsley and Anderson (1983), plotted with isotherms of the 1-atm solvus (after Lindsley, 1983) for Hole 504B, Legs 137/140 samples. Di' is diopside component, Hd' is hedenbergite, En' is enstatite, and Fs' is ferrosilite. Plot symbols are the same as for Figures 2, 3, and 4.

and Na-rich augite), in the Lower Pillow Alteration Zone (in three samples at 668 and 719 mbsf depth, one of which contains fassaite), in one sample from the transition zone between the pillow section and the sheeted dike complex, at 959 mbsf depth (Laverne, 1983; Laverne, 1987a), and in two samples from the dike complex cored during Leg 111, at 1436 and 1446 mbsf depth (Ishizuka, 1989). A deuteric origin was originally proposed for this secondary augite (Laverne, 1987a) because: (1) the process responsible for its formation does not depend on the depth; (2) this mineral occurs in each of the various zones characterized by very different alteration features (oxidative or reducing, high or low T, high or low water/rock ratio, more or less evolved fluid); (3) it formed prior to any other alteration minerals; (4) this mineral is anhydrous, in contrast to hydrated minerals in Hole 504B, which are known to be hydrothermal in origin.

Table 4. Representative plagioclase analyses from Hole 504B, Legs 137/140, keyed to spots on Plate 2A.

Core, section, interval (cm)	Analysis	Type	SiO$_2$	TiO$_2$	Al$_2$O$_3$	FeO	MnO	MgO	CaO	SrO	Na$_2$O	K$_2$O	BaO	CuO	Total	Si	Ti	Al	Fe	Mn
205R-1, 13–16	A143	Core	49.63	0.06	31.29	0.52	0.00	0.26	15.27	0.17	2.92	0.00	0.00	0.00	100.12	2.271	0.002	1.688	0.020	0.000
	A145	Core	49.70	0.03	31.76	0.30	0.00	0.26	15.83	0.18	2.58	0.00	0.02	0.05	100.64	2.261	0.001	1.703	0.011	0.000
	A144	Rim	46.19	0.00	34.46	0.12	0.00	0.01	17.92	0.11	1.28	0.00	0.03	0.03	100.09	2.124	0.000	1.868	0.005	0.000
	A147	Rim	45.10	0.00	35.21	0.15	0.00	0.02	18.92	0.14	0.88	0.00	0.00	0.06	100.48	2.075	0.000	1.910	0.006	0.000
	A148	Rim	45.42	0.01	35.97	0.14	0.03	0.00	19.19	0.15	0.63	0.00	0.00	0.00	101.54	2.066	0.000	1.929	0.005	0.001
	A146	Veinlet	66.10	0.02	22.20	0.20	0.00	0.00	2.29	0.20	10.43	0.02	0.04	0.00	101.50	2.868	0.001	1.136	0.007	0.000

If we interpret all the secondary Na, Ti diopside, and hedenbergite from Hole 504B as an early, high temperature, under low W/R ratio alteration from hydrothermal fluids derived from seawater, it means that such fluids were able to circulate everywhere in the hole, even in the pillow section. Why are these secondary clinopyroxene not more widespread?

We propose to interpret the green Na, Ti-rich clinopyroxene as well as melanite and fassaite from the pillow section as resulting from an alteration by late magmatic fluids (deuteric alteration), possibly mixed with small volumes of hydrothermal fluids. The colorless diopside, without anomalous Na concentrations, recovered during Legs 137/140 more probably has a hydrothermal origin.

Amphibole/Plagioclase

The more frequent occurrence of magnesio-hornblende (with increased Al and Ti concentrations) suggests higher maximum temperatures of alteration downhole (Raase, 1974; Laird and Albee, 1981). Independently, the first occurrence of secondary, hydrothermal calcic plagioclase suggests higher maximum temperatures as well. Recent experiments by Berndt and Seyfried (1993) have focused on the interaction of Na-Ca-Cl fluids and calcic plagioclase at 400°C and 400 bars. Results suggest that fluids with the chemical signature (particularly the Ca++/Na+ ratio) of modern black smokers from the East Pacific Rise are in equilibrium at these conditions with labradorite. Thus, equilibrium with calcic plagioclase such as anorthite requires either higher temperature or higher Ca++/Na+ in the fluid.

Fluid inclusions in calcic plagioclase generally exhibit homogenization temperatures in the range 150°–160°C, which, with an appropriate pressure correction, yield "trapping" temperatures of about 180°–190°C (Kelley et al., this volume). This is not interpreted as the actual range of trapping temperatures, even though the inclusions appear to be primary. Instead, these are similar to the present-day borehole temperature, and suggest that inclusions in plagioclase continue to re-equilibrate along cleavage microcracks to the ambient temperature and pressure conditions.

Geothermometry based upon the equilibrium partitioning of Na and Ca between calcic amphibole and plagioclase may qualitatively help constrain alteration temperatures (Spear, 1980). In the Legs 137/140 samples, amphiboles range from ferroactinolite or actinolite through actinolitic hornblende and magnesio-hornblende, and plagioclases vary from anorthite to albite in the same thin section. Petrographic evidence allows, however, that the earliest secondary plagioclase in vein halos, which is bytownite to anorthite, may have formed together with adjacent magnesio-hornblende in the same halos. According to the topology of the amphibole-plagioclase exchange, actinolitic hornblende and magnesio-hornblende can coexist with calcic labradorite through anorthite at temperatures exceeding 400°–500°C (Fig. 11).

Chlorite and Chlorite-Smectite

Chlorite-smectite exhibits several types of variation in the percentage of chlorite layers present. Chlorite-smectite in veins contains a greater proportion of chlorite layers than that replacing olivine in the host-rock of the same sample (Table 5), and chlorite-smectite in the rims of olivine pseudomorphs contains a greater percentage of chlorite layers than that at the cores of the pseudomorphs. In the intervals where relict olivine is present and where talc replaces olivine, chlorite-smectites contain relatively lower proportions of chlorite layers (1700–1820 mbsf, 1905–1938 mbsf, and 1980–1985 mbsf; Table 5; Fig. 8). Such variations can be explained by differences in temperature of reaction, or by variations in water-rock ratio and extent of reaction of the rocks, but in either case multiple stages of alteration are required.

Cathelineau and Nieva (1985) and Cathelineau (1988) have proposed a chlorite geothermometer based on variations in chlorite compositions with temperature in Los Azufres and other geothermal areas. Applying this geothermometer to the chlorite-smectites from Legs 137/140 suggests a positive correlation between percent chlorite layers and increasing temperature (Fig. 12). This would imply higher temperatures of formation of chlorite-smectite in veins compared to host rocks, and higher temperatures during formation of chlorite-smectite replacing the rims of olivines than for that replacing the cores of olivine. The lower proportions of chlorite layers in chlorite-smectite in the zones where relict olivine is present and where talc replaces olivine also implies lower temperatures of formation of chlorite-smectite in these zones. Several problems exist with this geothermometer, however. Taking into account the errors involved in deriving the correlation for the geothermometer, the calculated temperatures can vary by +50°C. Moreover, chlorites from other geothermal areas do not all agree with the Los Azufres data (Cathelineau and Nieva, 1985). The data used to establish the "chlorite" geothermometer are actually analyses of chlorite-smectites: the presence of Na and Ca in the analyses were regarded as "contaminants" and discarded, when in actuality these indicate the presence of smectite layers and chlorite-smectite rather than chlorite (Shau and Peacor, 1992). Thus the chlorite geothermometer is really a chlorite-smectite geothermometer, and implies that chlorite-smectites are thermodynamic phases in equilibrium with rocks and fluids at the given temperatures, which is probably not the case for chlorite-smectite from Leg 140.

Even though the calculated range of temperature of chlorite and chlorite-smectite can be wide because of the various modes of occurrence within single samples, some significant variations with depth occur. Three zones of maximum higher temperature are clearly distinguished, at 1630–1650, 1820, and 1980 mbsf. The 1630 and 1820 mbsf depths correspond to that where more Ti-rich and/or aluminous higher-temperature amphiboles occur.

An alternative explanation for variations in the percentage of chlorite layers in chlorite-smectite is that such variations are a function of reaction progress, reflecting the water/rock ratio and the kinetics of reaction of various phases in the rocks (Alt, 1984; Alt et al., 1985). Olivine is the first phase in the rocks to react with hydrothermal fluids. Thus, at very low water/rock ratios talc can form by simple hydration of olivine. This is borne out by the occurrence of relict olivine and talc replacing olivine in zones within the sheeted dikes where the rocks are only slightly altered and the abundance of veins is low from both core observations and logging measurements of the borehole walls (e.g., 1189–1319 mbsf, 1700–1820 mbsf, 1905–1938 mbsf, and 1980–1985 mbsf). At greater extents of reaction, plagio-

Table 4 (continued).

Mg	Ca	Sr	Na	K	Ba	Cu	Total	% An
0.018	0.749	0.005	0.259	0.000	0.000	0.000	5.012	74.3
0.018	0.772	0.005	0.228	0.000	0.000	0.002	5.000	77.2
0.001	0.883	0.003	0.114	0.000	0.001	0.001	4.999	88.6
0.001	0.933	0.004	0.079	0.000	0.000	0.002	5.009	92.2
0.000	0.935	0.004	0.056	0.000	0.000	0.000	4.997	94.4
0.000	0.106	0.005	0.878	0.001	0.001	0.000	5.003	10.8

Figure 11. Topology of equilibrium between calcic amphibole and plagioclase, modified after Spear (1980). The ordinate corresponds to the plagioclase composition (% anorthite component given along the right-hand edge). The abscissa value is calculated from the amphibole formula, where B represents the B-site (or M4 site). Generally, Hole 504B magnesio-hornblendes plot with a value of 1 to 3, actinolites plot at values above 4, and actinolitic hornblendes plot in between. The heavy curved line at the top depicts the calcic plagioclase solvus. Note that according to empirical temperature data from regionally metamorphosed rocks (temperatures labeled on diagram), the equilibrium coexistence of hornblende and anorthite-bytownite suggests temperatures exceeding 500°C. Likewise, equilibrium coexistence of actinolitic-hornblende or actinolite with anorthite-bytownite suggests temperatures of 300°–500°C. Three electron microprobe analyses of plagioclase and two of hornblende from Sample 137-504B-176R-1 (Piece 3) are shown as heavy dashed lines. Their intersections are marked with filled circles. The actual location of these intersections is quite uncertain, however, because the value of the abscissa is poorly determined with electron microprobe analyses. Application of the constraints shown here are discussed more fully in the text.

clase is altered, releasing Al, which is required to form chlorite. Thus, depending upon the extent of reaction and availability of Al, various proportions of chlorite will form in chlorite-smectite. The occurrence of greater percentages of chlorite in chlorite-smectite in alteration halos around veins than in the host rock is consistent with this interpretation: water/rock ratios and the extent of reaction of the rocks were greater in the alteration halos than in the host rocks, farther from the solutions circulating along fractures. The influence of reaction progress on secondary mineralogy could also be recorded as variations in Fe content in the phyllosilicates due to variations in fluid composition (e.g., progressive alteration of titanomagnetite to sphene should release Fe).

Figure 12. Plot of temperature (calculated using the Cathelineau geothermometer) vs. X (the proportion of chlorite to swelling component; Bettison and Schiffman, 1988) for Legs 137/140 chlorite and mixed-layer chlorite-smectite.

DISCUSSION

Alteration Style

Hydrothermal alteration is widespread, yet markedly heterogeneous, within the lower sheeted dike section sampled during Legs 137/140. On the scale of lithologic units sampled by the drill core (i.e., meter-scale and larger), variations in the intensity of hydrothermal alteration result in intervals that contain relict fresh olivine, fresh olivine mantled by talc alteration, or talc pseudomorphs of olivine. These intervals experienced restricted exposure to hydrothermal fluid such that the integrated water:rock ratio (W/R) must have been very much less than unity (down to zero according to $\delta^{18}O$ data [Agrinier et al., this volume]). The total volume percent of alteration minerals in olivine, talc-bearing zones is low. Point count data recorded for 133 thin sections (Shipboard Scientific Party, 1992b) show that the average total percent alteration of 44 talc-bearing thin sections is 15 vol% (range 3%–32%), whereas the average for 89 talc-free thin sections is 34 vol% (range 0%–94%).

On a finer scale, heterogeneous alteration is illustrated by the thin-section scale differences between vein halos and patches on the one hand and "background" altered dolerite on the other hand. Typically, halos and patches consist of greater than about 40 vol% alteration phases, whereas the normal dolerite alteration varies from near zero (unusually) to about 40 vol%. In the more highly altered background dolerite and in the halos/patches, olivine is completely altered, and chlorite and amphibole dominate the secondary phases. Talc is absent. This alteration heterogeneity at the 1- to 10-cm scale reflects restricted access of hydrothermal fluids along fractures and other more tortuous permeability paths (e.g., interconnected zones of high primary porosity, perhaps due to gas vesicles, segregation vesicles, or diktytaxitic shrinkage void space). The $\delta^{18}O$ values indicate a higher W/R ratio (>0.7) in these permeable zones (Agrinier et al., this volume). Fluid mass transport into the host dolerite adjacent to these permeable features resulted in relatively restricted, centimeter-scale halos and patches. This mass transport was probably chiefly grain boundary diffusion, because a more substantial advective flow of hydrothermal fluid would have produced more pervasive heavy alteration. Hence, highly localized variations, on the scale of centimeters, in the proportions of secondary phases must reflect spatial and temporal variations in the extent of fluid-rock interaction, rather than temperature and/or pressure variations.

A final aspect of the heterogeneity of hydrothermal alteration is the lithologic control on alteration style. During the coring of steeply dipping sheeted dikes, dike margins and dike interiors were repeat-

Table 5. Representative chlorite and chlorite-smectite analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	Expanded depth	Standard deviation	Occurrence	Temperature (°C)	X	SiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	TiO2
173R-1, 77–79	B2174	1573.1	0.52	ol	264	0.95	28.58	16.79	22.94	0.19	18.37	0.12	0.00	0.03	0.10
	B2181	1573.1	0.52	p	290	1.00	27.65	17.48	23.88	0.25	17.75	0.05	0.04	0.05	0.09
175R-1, 1–5	B5126	1587.1	1.12	ol	195	0.69	31.14	16.12	22.54	0.00	16.87	0.78	0.07	0.02	0.02
	B5127	1587.1	1.12	ol	204	0.81	30.97	15.49	22.31	0.13	18.56	0.46	0.00	0.03	0.00
	B5128	1587.1	1.12	pl	262	0.90	28.83	17.55	23.68	0.11	17.48	0.15	0.00	0.03	0.03
176R-1, 15–17	A5	1596.4	0.51	v	298	0.98	27.85	18.30	23.64	0.14	18.15	0.17	0.00	0.02	0.08
	A11	1596.4	0.51	v	292	0.95	28.02	18.36	22.64	0.15	18.33	0.14	0.05	0.00	0.05
177R-1, 11–15	B2106	1606.2	0.81	v	269	0.98	28.81	17.08	22.11	0.16	19.54	0.08	0.05	0.00	0.00
180M-1, 74–78	B5085	1619.7	0.20	p	200	0.77	30.99	16.04	22.71	0.16	17.46	0.35	0.05	0.07	0.04
	B5086	1619.7	0.20	p	246	0.83	28.60	17.20	23.65	0.15	15.89	0.22	0.02	0.01	0.02
186R-1, 140–143	B3106	1630.1	0.36	p	252	0.83	30.10	18.86	21.73	0.17	18.28	0.01	0.02	0.00	0.05
	B3109	1630.1	0.36	v	216	0.80	30.66	15.94	20.46	0.15	19.62	0.66	0.05	0.01	0.03
186R-2, 25–28	A37	1631.4	0.25	p	311	1.00	27.60	18.96	21.50	0.24	19.43	0.07	0.00	0.01	0.00
189R-1, 105–106	B2010	1652.9	0.15	ol	183	0.74	31.05	15.27	22.75	0.06	16.88	0.41	0.01	0.00	0.00
	B2012	1652.9	0.15	ol	180	0.72	31.01	14.99	21.93	0.14	17.05	0.53	0.00	0.00	0.00
189R-1, 106–110	V5152	1653.0	0.15	v	301	0.99	27.28	18.20	25.31	0.16	16.60	0.07	0.00	0.00	0.04
189R-2, 11–13	B2024	1653.3	0.15	cpx	276	0.94	28.58	16.34	21.77	0.14	19.22	0.38	0.00	0.00	0.05
189R-2, 76–79	B2162	1654.0	0.15	cpx	291	0.96	27.83	17.99	23.42	0.26	17.75	0.10	0.01	0.00	0.05
	B2166	1654.0	0.15	cpx	279	0.95	28.61	17.30	21.27	0.11	19.50	0.20	0.02	0.00	0.04
191R-1, 145–148	B3057	1670.5	0.44	ol	173	0.66	32.59	16.03	21.23	0.07	17.87	0.66	0.05	0.08	0.00
194R-1, 59–61	A55	1684.6	0.80	p	305	0.91	27.75	19.39	21.18	0.11	18.52	0.31	0.07	0.02	0.08
194R-1, 84–87	B5029	1686.7	0.76	ol	93	0.44	35.42	14.27	19.15	0.20	17.81	1.78	0.07	0.00	0.00
	B5030	1686.7	0.76	ol	218	0.76	30.52	17.33	21.54	0.12	17.59	0.27	0.00	0.04	0.02
195R-1, 7–8	B5120	1696.5	1.32	ol	228	0.78	29.86	17.03	21.40	0.05	17.71	0.38	0.00	0.04	0.06
	B5122	1696.5	1.32	ol	192	0.65	30.96	16.66	22.62	0.18	15.59	0.69	0.05	0.02	0.03
196R-1, 29–33	B3081	1700.5	0.88	ol	228	0.80	30.41	17.05	21.78	0.14	18.32	0.33	0.01	0.08	0.00
	B3082	1700.5	0.88	ol	212	0.78	31.00	16.34	20.86	0.13	18.94	0.42	0.05	0.07	0.03
197R-1, 44–46	B3075	1704.9	0.53	ol.c	190	0.71	31.31	15.86	22.44	0.07	17.30	0.63	0.07	0.26	0.00
	B3077	1704.9	0.53	ol.r	261	0.90	28.99	17.34	22.01	0.23	18.62	0.21	0.10	0.11	0.00
200R-1, 62–65	B4040	1729.8	0.20	v	284	0.97	28.34	17.86	20.41	0.11	20.10	0.12	0.02	0.00	0.08
200R-3, 81–84	B5037	1735.3	0.25	ol	261	0.92	29.37	17.53	19.66	0.14	20.51	0.15	0.00	0.00	0.01
	B5038	1735.3	0.25	ol	288	0.95	28.36	18.19	19.80	0.18	20.28	0.24	0.00	0.00	0.07
200R-3, 108–112	V6174	1736.0	0.24	ol.r	223	0.84	29.82	16.43	15.29	0.20	21.52	0.11	0.00	0.01	0.10
	V6177	1736.0	0.24	cpx	195	0.71	30.92	16.38	19.43	0.15	19.43	0.56	0.06	0.00	0.13
201R-1, 0–4	B3127	1739.3	1.30	ol	251	0.81	30.14	17.32	17.33	0.22	21.63	1.00	0.00	0.00	0.05
	B4009	1739.3	1.30	ol	60	0.33	36.16	12.72	23.31	0.12	14.99	2.66	0.10	0.08	0.00
	B4010	1739.3	1.30	ol.r	133	0.52	33.06	14.27	23.76	0.15	15.27	1.75	0.13	0.00	0.00
202R-1, 53–55	B5087	1748.6	0.11	ol	226	0.80	29.89	16.76	19.36	0.15	19.03	0.31	0.05	0.00	0.00
	B5088	1748.6	0.11	ol	161	0.59	32.17	16.16	19.09	0.20	17.48	0.81	0.08	0.00	0.00
205R-1, 6–9	B5104	1757.1	0.11	p	247	0.85	29.29	16.89	19.91	0.14	19.41	0.50	0.04	0.02	0.05
	B5105	1757.1	0.11	p	282	0.97	28.19	17.67	20.60	0.07	19.77	0.05	0.00	0.00	0.00
	B5106	1757.1	0.11	v	285	0.96	27.78	17.82	21.59	0.14	18.52	0.04	0.03	0.03	0.09
	B5111	1757.1	0.11	ol	224	0.76	30.47	16.76	20.23	0.18	19.06	0.86	0.08	0.00	0.02
208R-2, 76–81	B3103	1785.3	0.39	ol.c	141	0.65	34.36	15.12	16.89	0.16	21.30	0.51	0.01	0.00	0.00
	B3104	1785.3	0.39	ol.r	243	0.86	30.12	17.34	16.84	0.26	21.64	0.15	0.03	0.00	0.02
	B5009	1785.3	0.39	ol	206	0.79	31.26	16.08	19.95	0.04	19.95	0.49	0.02	0.00	0.00
	B5014	1785.3	0.39	ol.r	222	0.86	30.56	15.97	19.71	0.13	20.53	0.36	0.03	0.00	0.00
	B5025	1785.3	0.39	ol.c	135	0.53	34.04	14.49	18.83	0.16	19.35	1.93	0.04	0.00	0.00
	B5026	1785.3	0.39	ol.c	173	0.68	32.32	15.22	19.73	0.13	19.40	1.02	0.04	0.05	0.05
208R-3, 1–4	A74	1787.5	0.13	p	262	0.88	28.85	17.71	17.78	0.06	20.47	0.25	0.07	0.00	0.10
	A78	1787.5	0.13	p	226	0.76	31.16	17.11	17.65	0.17	21.29	0.99	0.03	0.01	0.08
209R-2, 108–111	B6022	1791.7	0.35	p	286	0.90	28.09	18.65	19.04	0.07	19.58	0.16	0.03	0.01	0.00
	B6026	1791.7	0.35	p	300	0.94	27.62	18.56	18.41	0.19	20.21	0.18	0.04	0.01	0.01
	B6052	1791.7	0.35	p	266	0.87	29.11	18.39	18.82	0.20	19.90	0.11	0.03	0.00	0.03
209R-2, 146–149	V6178	1794.7	0.11	ol	222	0.81	30.23	16.64	18.50	0.10	19.83	0.28	0.02	0.00	0.00
	V6181	1794.7	0.11	ol	202	0.76	30.84	16.29	18.88	0.17	19.18	0.26	0.02	0.00	0.03
	B6013	1794.7	0.11	v	299	0.96	27.03	18.22	21.64	0.22	17.64	0.08	0.00	0.02	0.04
210R-1, 56–60	B3114	1795.9	0.16	ol.c	199	0.78	31.20	15.98	18.12	0.13	20.37	0.35	0.00	0.01	0.00
	B3115	1795.9	0.16	ol.c	187	0.76	31.41	15.76	17.03	0.17	20.46	0.22	0.04	0.00	0.02
212R-1, 61–65	B5095	1812.3	0.32	ol out halo	219	0.82	29.87	16.10	23.55	0.03	16.82	0.25	0.01	0.03	0.00
	B5096	1812.3	0.32	ol out halo	249	0.88	28.60	16.64	24.67	0.08	16.30	0.22	0.00	0.02	0.00
	B5097	1812.3	0.32	ol in halo	252	0.89	29.08	16.73	21.25	0.02	19.14	0.33	0.04	0.05	0.00
	B5098	1812.3	0.32	ol in halo	226	0.79	29.81	16.86	22.43	0.10	17.16	0.43	0.00	0.04	0.00
214R-2, 0–5	B3119	1820.9	0.14	ol	237	0.86	30.21	17.26	19.26	0.24	20.25	0.16	0.03	0.00	0.04
	B3121	1820.9	0.14	ol	259	0.90	29.75	17.64	19.10	0.29	20.91	0.20	0.02	0.00	0.06
214R-2, 29–32	P0037	1821.4	0.14	pl	286	0.96	27.86	17.84	20.25	0.14	19.48	0.10	0.01	0.00	0.00
215R-1, 43–46	B5117	1825.4	0.45	p	267	0.88	29.54	17.97	20.76	0.23	19.87	0.42	0.06	0.04	0.14
	B5118	1825.4	0.45	p	295	0.98	27.61	18.29	20.89	0.23	19.04	0.01	0.00	0.00	0.09
216R-1, 25–28	A83	1831.3	0.96	int	280	0.89	27.79	18.33	23.26	0.18	16.54	0.10	0.00	0.00	0.03
	A84	1831.3	0.96	int	261	0.84	29.12	18.71	19.85	0.20	18.70	0.12	0.00	0.00	0.00
216R-1, 58–60	P0057	1835.1	0.88	v	303	0.96	26.54	18.32	22.45	0.28	16.78	0.03	0.01	0.00	0.01
	B2035	1835.1	0.88	ol	257	0.94	28.91	16.83	22.67	0.28	18.36	0.06	0.01	0.00	0.05
	B2036	1835.1	0.88	ol	238	0.77	28.94	17.08	21.24	0.25	16.80	0.48	0.03	0.03	0.08
218R-1, 20–23	B3043	1853.9	1.31	ol/p	180	0.67	32.41	15.99	20.75	0.17	18.68	1.00	0.06	0.00	0.06
	B3045	1853.9	1.31	v	242	0.82	29.37	17.12	21.85	0.16	17.78	0.41	0.01	0.00	0.02
	B3046	1853.9	1.31	v	273	0.84	28.74	18.75	21.91	0.19	17.60	0.32	0.02	0.00	0.00
222R-1, 129–132	P0085	1893.5	0.44	ol	263	0.88	29.01	17.92	22.20	0.36	17.96	0.15	0.00	0.03	0.02
223R-1, 9–11	B3029	1896.8	1.18	ol/p	206	0.69	30.39	15.95	23.47	0.17	16.19	1.16	0.05	0.01	0.03
224R-1, 27–30	B5053	1905.6	0.75	ol	266	0.93	28.17	16.89	24.26	0.15	16.92	0.21	0.04	0.00	0.03
	B5056	1905.6	0.75	ol	231	0.84	28.80	15.87	23.39	0.34	16.26	0.31	0.00	0.00	0.00
225R-1, 126–129	B5039	1916.9	0.36	int	251	0.86	28.80	17.32	22.39	0.10	17.34	0.15	0.03	0.00	0.00
	B5040	1916.9	0.36	int	212	0.85	30.70	15.85	20.36	0.23	19.74	0.15	0.00	0.00	0.08
	B5044	1916.9	0.36	cpx	144	0.59	34.09	14.53	19.12	0.13	20.17	1.62	0.10	0.00	0.07
226R-1, 99–102	B2041	1921.4	0.10	ol/int	254	0.94	29.62	16.99	18.65	0.12	21.55	0.08	0.04	0.02	0.00
	B2044	1921.4	0.10	ol	262	0.92	29.59	17.15	17.72	0.24	21.73	0.10	0.02	0.00	0.01
	B2045	1921.4	0.10	ol	161	0.66	33.30	14.93	17.45	0.06	21.26	1.14	0.06	0.00	0.00
226R-3, 5–9	B2077	1924.0	0.07	p	237	0.91	29.77	16.25	18.14	0.21	21.20	0.08	0.01	0.00	0.01
	B2078	1924.0	0.07	p	269	0.90	28.57	17.39	18.33	0.10	20.48	0.37	0.05	0.00	0.02
228R-1, 58–60	B5113	1940.9	0.92	ol.c	93	0.49	35.51	13.64	19.01	0.00	18.80	1.39	0.07	0.05	0.00
	B5115	1940.9	0.92	v	224	0.90	30.64	15.85	19.80	0.16	21.22	0.23	0.00	0.00	0.00
236R-1, 0–4	P0061	1980.9	0.14	ol.r	293	1.00	28.45	18.21	18.01	0.11	22.15	0.03	0.00	0.00	0.03
	P0062	1980.9	0.14	ol.c	157	0.62	33.17	15.15	17.09	0.16	20.59	1.25	0.03	0.00	0.03
	P0063	1980.9	0.14	ol.c	132	0.53	33.72	14.06	17.07	0.00	20.15	1.89	0.05	0.00	0.04
	P0064	1980.9	0.14	ol.r	272	0.96	28.41	17.21	18.12	0.06	21.19	0.07	0.00	0.02	0.00
236R-1, 30–32	B3136	1981.8	0.27	ol	149	0.58	32.93	14.90	24.29	0.19	15.65	1.38	0.11	0.03	0.05
	B3137	1981.8	0.27	ol	171	0.59	31.72	14.83	24.77	0.14	15.26	1.67	0.04	0.06	0.09
236R-1, 57–60	B3087	1982.5	0.28	ol	294	0.94	28.53	19.06	16.38	0.01	22.17	0.13	0.01	0.00	0.09
237R-1, 24–26	B3009	1991.1	0.90	ol	183	0.66	31.93	15.10	21.45	0.23	18.37	1.55	0.04	0.00	0.01
	B3012	1991.1	0.90	ol	223	0.82	30.13	16.44	21.15	0.19	18.54	0.27	0.00	0.00	0.00

Notes: ol = olivine replacement; ol.c = olivine core replacement; ol.r = olivine rim replacement; pl = plagioclase replacement; cpx = clinopyroxene replacement; v = vein; p = patch; int = interstitial.

Table 5 (continued).

Core, section, interval (cm)	Cr$_2$O$_3$	Cl	ZnO	Total	Si	Al^{IV}	Al^{VI}	Alt	Fe	Mn	Mg	Ca	Na	K	Ti	Cr
173R-1, 77–79	0.07	0.00	0.04	87.23	5.920	2.080	2.019	4.099	3.974	0.033	5.672	0.027	0.000	0.008	0.016	0.011
	0.06	0.00	0.04	87.34	5.816	2.184	2.148	4.333	4.200	0.045	5.565	0.011	0.016	0.013	0.014	0.010
175R-1, 1–5	0.40	0.00	0.19	88.15	6.005	1.995	1.668	3.663	3.635	0.000	4.849	0.161	0.026	0.005	0.003	0.061
	0.32	0.01	0.02	88.30	6.101	1.899	1.697	3.596	3.676	0.022	5.450	0.097	0.000	0.008	0.000	0.050
	0.01	0.00	0.17	88.04	5.861	2.139	2.066	4.205	4.026	0.019	5.297	0.033	0.000	0.008	0.005	0.002
176R-1, 15–17	0.00	nd	nd	88.35	5.738	2.262	2.182	4.443	4.073	0.024	5.574	0.038	0.000	0.005	0.012	0.000
	0.02	nd	nd	87.76	5.749	2.251	2.189	4.440	3.885	0.026	5.606	0.031	0.020	0.000	0.008	0.003
177R-1, 11–15	0.03	0.00	0.00	87.86	5.916	2.084	2.049	4.133	3.797	0.028	5.980	0.018	0.020	0.000	0.000	0.005
180M-1, 74–78	0.14	0.03	0.15	88.19	6.067	1.933	1.768	3.701	3.718	0.027	5.095	0.073	0.019	0.017	0.006	0.022
	0.00	0.01	0.03	85.80	5.870	2.130	2.030	4.160	4.059	0.026	4.861	0.048	0.008	0.003	0.003	0.000
186R-1, 140–143	0.05	0.00	0.00	89.27	5.841	2.159	2.155	4.313	3.527	0.028	5.288	0.002	0.008	0.000	0.007	0.008
	0.00	0.01	0.14	87.73	6.017	1.983	1.703	3.686	3.358	0.025	5.739	0.139	0.019	0.003	0.004	0.000
186R-2, 25–28	0.00	nd	nd	87.81	5.683	2.317	2.284	4.601	3.702	0.042	5.963	0.015	0.000	0.003	0.000	0.000
189R-1, 105–106	0.40	0.03	0.00	86.86	6.135	1.865	1.691	3.556	3.759	0.010	4.971	0.087	0.004	0.000	0.000	0.062
	0.56	0.00	0.05	86.26	6.139	1.861	1.636	3.497	3.631	0.023	5.031	0.112	0.000	0.000	0.000	0.088
189R-1, 106–110	0.00	0.03	0.00	87.69	5.731	2.269	2.237	4.506	4.447	0.028	5.198	0.016	0.000	0.000	0.006	0.000
189R-2, 11–13	1.76	0.04	0.21	88.49	5.921	2.079	1.910	3.989	3.772	0.025	5.935	0.084	0.000	0.000	0.008	0.288
189R-2, 76–79	0.15	0.02	0.00	87.58	5.777	2.223	2.178	4.401	4.066	0.046	5.492	0.022	0.004	0.000	0.008	0.025
	0.95	0.00	0.00	88.00	5.866	2.134	2.046	4.180	3.647	0.019	5.959	0.044	0.008	0.000	0.006	0.154
191R-1, 145–148	0.65	0.00	0.14	89.37	6.093	1.907	1.624	3.532	3.319	0.011	4.979	0.132	0.018	0.019	0.000	0.096
194R-1, 59–61	0.03	nd	nd	87.46	5.617	2.383	2.243	4.626	3.586	0.019	5.588	0.067	0.027	0.005	0.012	0.005
194R-1, 84–87	0.09	0.00	0.00	88.79	6.196	1.804	1.137	2.942	2.801	0.030	4.643	0.334	0.024	0.000	0.000	0.012
	0.12	0.00	0.08	87.63	5.948	2.052	1.929	3.980	3.511	0.020	5.110	0.056	0.000	0.010	0.003	0.018
195R-1, 7–8	0.16	0.00	0.04	86.73	5.924	2.076	1.905	3.981	3.550	0.008	5.237	0.081	0.000	0.010	0.009	0.025
	0.36	0.00	0.20	87.36	5.964	2.036	1.746	3.782	3.644	0.029	4.476	0.142	0.019	0.005	0.004	0.055
196R-1, 29–33	0.31	0.01	0.00	88.44	5.954	2.046	1.888	3.934	3.566	0.023	5.346	0.069	0.004	0.020	0.000	0.048
	0.44	0.00	0.00	88.28	6.031	1.969	1.777	3.746	3.394	0.021	5.492	0.088	0.019	0.017	0.004	0.068
197R-1, 44–46	0.07	0.00	0.23	88.24	6.036	1.964	1.640	3.603	3.618	0.011	4.971	0.130	0.026	0.064	0.000	0.011
	0.03	0.02	0.01	87.67	5.871	2.129	2.009	4.138	3.728	0.039	5.621	0.046	0.039	0.028	0.000	0.005
200R-1, 62–65	0.00	nd	nd	87.04	5.814	2.186	2.133	4.318	3.502	0.019	6.147	0.026	0.008	0.000	0.012	0.000
200R-3, 81–84	0.15	0.04	0.03	87.59	5.895	2.105	2.041	4.146	3.300	0.024	6.136	0.032	0.000	0.000	0.002	0.024
	0.14	0.01	0.00	87.27	5.768	2.232	2.128	4.360	3.368	0.031	6.148	0.052	0.000	0.000	0.011	0.023
200R-3, 108–112	0.00	0.00	0.07	83.55	6.020	1.980	1.929	3.909	2.582	0.034	6.476	0.024	0.000	0.003	0.015	0.000
	0.02	0.01	0.02	85.91	6.008	1.992	1.759	3.751	3.157	0.025	5.280	0.117	0.023	0.000	0.019	0.003
201R-1, 0–4	0.32	0.03	0.03	88.07	5.822	2.178	1.764	3.943	2.799	0.036	6.227	0.207	0.000	0.000	0.007	0.049
	0.00	nd	nd	90.14												
	0.20	nd	nd	88.59												
202R-1, 53–55	0.18	0.00	0.13	85.86	5.963	2.037	1.904	3.941	3.230	0.025	5.659	0.066	0.019	0.000	0.000	0.028
	0.05	0.00	0.10	86.14	6.047	1.953	1.627	3.580	3.001	0.032	4.897	0.163	0.029	0.000	0.000	0.007
205R-1, 6–9	0.03	0.02	0.13	86.43	5.889	2.111	1.891	4.002	3.348	0.024	5.817	0.108	0.016	0.005	0.008	0.005
	0.11	0.00	0.00	86.46	5.834	2.166	2.144	4.310	3.565	0.012	6.098	0.011	0.000	0.000	0.000	0.018
	0.02	0.03	0.00	86.09	5.796	2.204	2.178	4.382	3.767	0.025	5.760	0.009	0.012	0.008	0.014	0.003
	0.04	0.00	0.19	87.89	5.907	2.093	1.736	3.829	3.280	0.030	5.507	0.179	0.030	0.000	0.003	0.006
208R-2, 76–81	0.61	0.01	0.07	89.04	6.274	1.726	1.527	3.253	2.579	0.025	5.797	0.100	0.004	0.000	0.000	0.088
	0.34	0.00	0.10	86.84	5.950	2.050	1.987	4.037	2.782	0.044	6.372	0.032	0.011	0.000	0.003	0.053
	0.15	0.00	0.00	87.94	6.061	1.939	1.735	3.674	3.235	0.007	5.766	0.102	0.008	0.000	0.000	0.023
	0.16	0.02	0.12	87.59	6.058	1.942	1.789	3.731	3.268	0.022	6.066	0.076	0.012	0.000	0.000	0.025
	0.12	0.00	0.00	88.96	6.100	1.900	1.159	3.060	2.822	0.024	5.168	0.371	0.014	0.000	0.000	0.017
	0.03	0.00	0.00	87.99	6.096	1.904	1.479	3.383	3.112	0.021	5.454	0.206	0.015	0.012	0.007	0.004
208R-3, 1–4	0.02	nd	nd	85.31	5.835	2.165	2.056	4.221	3.007	0.010	6.171	0.054	0.027	0.000	0.015	0.003
	0.02	nd	nd	88.51	5.892	2.108	1.705	3.813	2.791	0.027	6.000	0.201	0.011	0.002	0.011	0.003
209R-2, 108–111	0.09	nd	nd	85.72	5.724	2.276	2.203	4.479	3.245	0.012	5.947	0.035	0.012	0.003	0.000	0.015
	0.41	nd	nd	85.64	5.701	2.299	2.216	4.515	3.178	0.033	6.218	0.040	0.016	0.003	0.002	0.067
	0.19	nd	nd	86.78	5.813	2.187	2.140	4.327	3.143	0.034	5.923	0.024	0.012	0.000	0.005	0.030
209R-2, 146–149	0.34	0.01	0.16	86.11	5.996	2.004	1.885	3.889	3.069	0.017	5.862	0.060	0.008	0.000	0.000	0.053
	0.36	0.00	0.19	86.22	6.059	1.941	1.831	3.772	3.102	0.028	5.617	0.055	0.008	0.000	0.004	0.056
	0.00	nd	nd	85.43	5.711	2.289	2.247	4.537	3.919	0.039	5.555	0.018	0.000	0.005	0.006	0.000
210R-1, 56–60	0.20	0.00	0.00	86.36	6.088	1.912	1.763	3.675	2.957	0.021	5.925	0.073	0.000	0.002	0.000	0.031
	0.35	0.00	0.00	85.46	6.139	1.861	1.769	3.630	2.784	0.028	5.960	0.046	0.015	0.000	0.003	0.054
212R-1, 61–65	0.35	0.00	0.14	87.15	6.028	1.972	1.856	3.829	3.974	0.005	5.059	0.054	0.004	0.008	0.000	0.056
	0.11	0.00	0.11	86.75	5.919	2.081	1.978	4.059	4.270	0.014	5.028	0.049	0.000	0.005	0.000	0.018
	0.06	0.00	0.00	86.70	5.916	2.084	1.927	4.011	3.615	0.003	5.804	0.072	0.016	0.013	0.000	0.010
	0.08	0.00	0.09	87.00	5.928	2.072	1.879	3.951	3.730	0.017	5.086	0.092	0.000	0.010	0.000	0.013
214R-2, 0–5	0.01	0.01	0.13	87.60	5.960	2.040	1.973	4.013	3.178	0.040	5.954	0.034	0.011	0.000	0.006	0.002
	0.22	0.00	0.01	88.20	5.897	2.103	2.018	4.121	3.166	0.049	6.178	0.042	0.008	0.000	0.009	0.034
214R-2, 29–32	0.11	nd	nd	85.79	5.792	2.208	2.163	4.371	3.521	0.025	6.037	0.022	0.004	0.000	0.000	0.018
215R-1, 43–46	0.13	0.00	0.11	89.27	5.820	2.180	1.993	4.172	3.421	0.038	5.835	0.089	0.023	0.010	0.021	0.020
	0.00	0.03	0.00	86.19	5.752	2.248	2.243	4.491	3.640	0.041	5.913	0.002	0.000	0.000	0.014	0.000
216R-1, 25–28	0.02	nd	nd	86.25	5.745	2.255	2.211	4.466	4.021	0.032	5.097	0.022	0.000	0.000	0.005	0.003
	0.00	nd	nd	86.70	5.785	2.215	2.164	4.380	3.298	0.034	5.537	0.026	0.000	0.000	0.000	0.000
216R-1, 58–60	0.08	nd	nd	84.50	5.682	2.318	2.304	4.622	4.020	0.051	5.355	0.007	0.004	0.000	0.002	0.014
	0.21	0.02	0.00	87.40	5.947	2.053	2.027	4.080	3.900	0.049	5.629	0.013	0.004	0.000	0.008	0.034
	0.24	0.00	0.15	85.32	5.856	2.144	1.928	4.073	3.594	0.043	5.067	0.104	0.012	0.008	0.012	0.038
218R-1, 20–23	0.04	0.00	0.00	89.16	6.043	1.957	1.557	3.514	3.236	0.027	5.192	0.200	0.022	0.000	0.008	0.006
	0.08	0.00	0.00	86.80	5.889	2.111	1.935	4.045	3.664	0.027	5.314	0.088	0.004	0.000	0.003	0.013
	0.15	0.00	0.00	87.68	5.729	2.271	2.134	4.405	3.653	0.032	5.229	0.068	0.008	0.000	0.000	0.024
222R-1, 129–132	0.22	nd	nd	87.87	5.839	2.161	2.089	4.250	3.737	0.061	5.388	0.032	0.000	0.008	0.003	0.035
223R-1, 9–11	0.08	0.03	0.00	87.53	5.924	2.076	1.589	3.664	3.826	0.028	4.704	0.242	0.019	0.002	0.004	0.012
224R-1, 27–30	0.10	0.00	0.00	86.77	5.877	2.123	2.029	4.152	4.233	0.027	5.261	0.047	0.016	0.000	0.005	0.016
	0.34	0.03	0.00	85.34	5.987	2.013	1.875	3.888	4.066	0.060	5.038	0.069	0.000	0.000	0.000	0.056
225R-1, 126–129	0.12	0.00	0.00	86.25	5.883	2.117	2.052	4.169	3.825	0.017	5.279	0.033	0.012	0.000	0.000	0.019
	0.11	0.00	0.00	87.22	6.109	1.891	1.827	3.717	3.388	0.039	5.855	0.032	0.000	0.000	0.012	0.017
	0.06	0.01	0.04	89.94	6.144	1.856	1.230	3.086	2.882	0.020	5.418	0.313	0.035	0.000	0.009	0.009
226R-1, 99–102	0.12	0.03	0.15	87.37	5.964	2.036	1.996	4.032	3.141	0.020	6.468	0.017	0.016	0.005	0.000	0.019
	1.14	0.03	0.06	87.79	5.947	2.053	2.010	4.062	2.979	0.041	6.510	0.022	0.008	0.000	0.002	0.181
	0.23	0.03	0.16	88.62	6.150	1.850	1.399	3.249	2.695	0.009	5.852	0.226	0.021	0.000	0.000	0.034
226R-3, 5–9	0.26	0.04	0.00	85.97	6.040	1.960	1.925	3.885	3.078	0.036	6.411	0.017	0.004	0.000	0.002	0.042
	0.25	0.00	0.15	85.71	5.829	2.171	2.010	4.181	3.127	0.017	6.228	0.081	0.020	0.000	0.003	0.040
228R-1, 58–60	0.49	0.00	0.33	89.29	6.303	1.697	1.157	2.853	2.822	0.000	4.974	0.264	0.024	0.011	0.000	0.069
	0.00	0.03	0.00	87.93	6.094	1.906	1.808	3.715	3.293	0.027	6.290	0.049	0.000	0.000	0.000	0.000
236R-1, 0–4	0.14	nd	nd	87.13	5.804	2.196	2.183	4.378	3.073	0.019	6.736	0.007	0.000	0.000	0.005	0.023
	0.14	nd	nd	87.61	6.109	1.891	1.397	3.288	2.632	0.025	5.652	0.247	0.011	0.000	0.004	0.020
	0.20	nd	nd	85.18	6.127	1.873	1.137	3.011	2.594	0.000	5.457	0.368	0.018	0.000	0.005	0.029
	0.10	nd	nd	85.18	5.882	2.118	2.081	4.199	3.138	0.011	6.539	0.016	0.000	0.005	0.000	0.016
236R-1, 30–32	0.12	0.05	0.22	89.92	6.097	1.903	1.348	3.251	3.761	0.030	4.319	0.274	0.039	0.007	0.007	0.018
	0.21	0.24	0.10	89.13	6.001	1.999	1.307	3.306	3.919	0.022	4.303	0.339	0.015	0.014	0.013	0.031
236R-1, 57–60	0.17	0.04	0.17	86.76	5.720	2.280	2.224	4.504	2.747	0.002	6.625	0.028	0.004	0.000	0.014	0.027
237R-1, 24–26	0.13	0.01	0.00	88.82	6.012	1.988	1.363	3.351	3.378	0.037	5.155	0.313	0.015	0.000	0.001	0.019
	0.25	0.00	0.02	86.99	6.010	1.990	1.875	3.865	3.528	0.032	5.512	0.058	0.000	0.000	0.000	0.039

edly encountered. Fracture intensity is demonstrably higher in the finer-grained dike-margin rocks, presumably because of the higher thermal contractional stresses experienced by aphanitic and fine-grained dike margins relative to medium-grained dike interiors. Thus, vein density and, by inference, the integrated W/R ratio are also higher in dike margin rocks. Significantly, the few veins bearing quartz and/or epidote occur in association with fine-grained rocks and aphanitic chilled margins.

Evidence from cross-cutting veins and mineral pseudomorphs indicates that many samples apparently underwent several episodes of hydrothermal alteration (Shipboard Scientific Party, 1992a, b). This could be due to the episodic nature of local heat sources in a dike swarm: each individual dike intrusion, or each episode of swarm intrusion, is capable of reestablishing a new hydrothermal system that cools the newly intruded material. Such episodicity means that "early" high-temperature minerals may postdate low-temperature minerals from a previous hydrothermal alteration. Nevertheless, for simplicity we may place the observed alteration minerals in a sequence of formation that begins at high temperature and continues to lower temperature with time. This sequence is frequently confirmed by geometrical evidences.

The earliest alteration, related to early fracture-controlled introduction of fluid (probably mixed deuteric and hydrothermal fluids) resulted in the restricted development of secondary Na- and Ti-rich diopside at temperatures between about 500°C and 600°C. This alteration is closely followed by the development of vein halos that contain magnesio-hornblende and secondary anorthite or bytownite plagioclase, with estimated temperatures exceeding 400°–500°C. Very small amounts of secondary diopside without anomalous Na or Ti occur locally in veinlets and patches and possibly formed prior to hornblende and anorthite, suggesting a water/rock ratio low and then higher.

The second alteration stage is characterized by the growth of actinolite and actinolitic hornblende with chlorite in veins; albite forming veinlets that crosscut primary igneous plagioclase as well as secondary calcic plagioclase; and chlorite, chlorite-smectite, or talc after olivine in lower permeability rocks. This stage is generally lower temperature, estimated at around 250°–320°C.

The third stage is represented by epidote and quartz in veins and vugs and minor epidote after host-rock plagioclase. Oxygen isotope analyses of two pairs of epidote and quartz from veins of the Legs 137/140 section indicate temperatures of 310°–320°C for these minerals (Alt et al., this volume) and are similar to temperatures estimated from quartz and epidote from the upper dikes and transition zone (Alt et al., 1986b).

During a fourth stage, anhydrite crystallized, probably directly from heated seawater.

Finally, laumontite and prehnite formed at temperatures probably less than or equal to about 250°C.

Origin of Hydrothermal Fluid

Hydrothermal fluids trapped in fluid inclusions in secondary plagioclase and, rarely, in quartz, represent aqueous solutions with seawater-like salinities (Kelley et al., this volume). Many inclusions bear dissolved gas (possibly CO_2 or CH_4), though at concentrations and pressures too low to form a liquid gas phase at room temperature. The most likely origin of such fluids is a hydrothermal, modified seawater with an unknown, most probably very small magmatic contribution.

Independent evidence that the hydrothermal fluid was seawater is the stable isotopic signature of altered rocks (Agrinier et al., this volume). Oxygen isotopic whole-rock values are typically shifted down from the primary magmatic value of +5.6‰, resulting from the high-temperature (>250°C) oxygen isotopic exchange with hydrothermal seawater (which is probably about 0‰ to +2‰; e.g., Stakes and O'Neill, 1982)

Chlorine concentrations in amphiboles are typical for seawater-altered, amphibole-bearing deep crustal rocks from the ocean, wherein

actinolite has minor Cl (less than 0.05 wt% Cl), hornblendes typically have 0.1 to 1.5 wt% Cl, and rare Cl-rich hornblendes contain up to about 4.0 wt% Cl (e.g., Vanko, 1986; Vanko and Stakes, 1991). In the Legs 137/140 rocks, actinolite is Cl-poor, and hornblende contains up to about 0.5 wt% Cl. The lack of Cl-rich amphibole may indicate that unusually briney hydrothermal fluids did not develop in the lower sheeted dikes during water-rock interaction, at least in this area.

The mere volume of hydrothermal minerals observed in the sheeted dikes of Hole 504B may require a seawater source of the fluid as opposed to a magmatic source. A typical estimate of the total volume of alteration minerals based on thin-section point counts (Shipboard Scientific Party, 1992b) is about 30 vol%. If these minerals are approximated by amphibole (2 wt% water) and chlorite (12 wt% water) in a 5:1 ratio, the dolerite contains an estimated 1.1 wt% water, which exceeds most estimates of the water content of typical primitive mid-ocean-ridge basalt.

Implications for Crustal Alteration

Several results of the present study are significant in contributing to our understanding of the alteration of oceanic crust. First, all of Hole 504B has undergone hydrothermal alteration, and the present results extend those of previous studies that described the low-temperature oxidative alteration of the upper pillowed section, the low-temperature reducing alteration of the lower pillows, and the greenschist-like alteration of the transition zone and the sheeted dikes. The lower sheeted dikes of Legs 137/140 experienced higher temperature alteration in general, as evidenced by more prevalent actinolitic hornblende and, especially, abundant magnesio-hornblendes.

With the exception of the stockwork-like alteration in the transition zone (Honnorez et al., 1985) and minor quartz-epidote assemblages along dike margins, practically all of the sheeted dike alteration results from non-focused, pervasive fluid-rock interaction as opposed to focused, high-temperature, high W/R discharge alteration. In the terminology of "discharge" and "recharge" alteration as described by Harper et al. (1988) for the Josephine ophiolite, the Hole 504B dike alteration is probably within the "recharge," or even within a "reaction zone" milieu. The characteristics of this reaction zone, then, include an initial high-temperature development of secondary clinopyroxene, followed closely by a calcic plagioclase-hornblende assemblage (amphibolite facies), then a pervasive greenschist-like actinolite-chlorite-sodic plagioclase assemblage. Finally, interaction with cooler fluids caused the crystallization of zeolites, prehnite, and anhydrite.

The alteration style described here for Hole 504B differs in significant ways from alteration described from ophiolite sections and from other oceanic sample suites. One major new discovery in Hole 504B is the presence of hydrothermal anorthite-bytownite, in association with magnesio-hornblende in amphibole vein halos. This assemblage may partly verify the recent prediction (Berndt and Seyfried, 1993) that the plagioclase that should be found in the reaction zone for modern black smoker fluids is calcic labradorite. This prediction is based upon experiments reacting plagioclase and Na-Ca-Cl fluids, and is understood as a consequence of (1) the high temperatures inferred for the reaction zone, such that sodic plagioclases are not stable, and (2) the fact that reacted seawater, having already affected the formation of secondary albite at lower temperature, is enriched in calcium by the time the reaction zone is reached. The discovery of secondary anorthite-bytownite is an extension of recent descriptions of intermediate secondary plagioclase in other oceanic sample suites (e.g., oligoclase and andesine in Hole 735B gabbros [Vanko and Stakes, 1991]), and oligoclase in Oceanographer Transform gabbros [Vanko et al., 1992]).

CONCLUSIONS

1. Hydrothermal alteration is widespread, but heterogeneous, in the studied dike section. This heterogeneity, which is related to the

Table 6. Representative talc and mixed-layer talc-chlorite analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	Cr_2O_3	Total	Si	Al	Al^{IV}	Al^{VI}	Fe	Mn	Mg	Ca	Na	K	Ti	Cr	Total	IV	VI
175R-1, 1–5	B5125	62.65	0.22	2.03	0.00	29.64	0.06	0.00	0.02	0.02	0.01	94.65	8.028	0.033	0.000	0.033	0.218	0.000	5.661	0.008	0.000	0.003	0.002	0.001	13.988	8.028	5.926
200R-1, 62–65	B4015	60.68	0.30	2.32	0.00	29.04	0.13	0.07	0.04	0.00	0.00	92.58	7.977	0.047	0.023	0.024	0.255	0.000	5.690	0.018	0.018	0.007	0.000	0.000	14.058	8.000	6.012
	B4017	61.39	0.63	2.64	0.00	29.96	0.11	0.06	0.00	0.00	0.00	94.79	7.901	0.096	0.096	0.000	0.284	0.000	5.747	0.015	0.015	0.000	0.000	0.000	14.154	7.997	6.061
	B4020	57.76	1.94	7.59	0.00	25.52	0.74	0.04	0.06	0.00	0.10	93.75	7.733	0.306	0.267	0.040	0.850	0.000	5.092	0.106	0.010	0.010	0.000	0.011	14.425	8.000	6.119
	B4025	53.83	3.92	8.85	0.09	22.97	1.33	0.06	0.05	0.00	0.03	91.13	7.502	0.644	0.498	0.147	1.032	0.011	4.771	0.199	0.016	0.009	0.000	0.003	14.831	8.000	6.187
	B4026	58.80	1.41	6.79	0.00	25.95	0.45	0.03	0.00	0.00	0.11	93.54	7.836	0.222	0.164	0.057	0.757	0.000	5.154	0.064	0.008	0.000	0.012	14.273	8.000	6.052
	B4027	60.50	0.21	2.40	0.13	29.14	0.11	0.03	0.00	0.00	0.07	92.59	7.963	0.033	0.033	0.000	0.264	0.014	5.716	0.016	0.008	0.000	0.000	0.007	14.053	7.996	6.025
200R-2, 18–24	V3069	62.04	0.32	4.48	0.04	28.40	0.03	0.07	0.00	0.00	0.00	95.38	7.989	0.049	0.011	0.037	0.482	0.004	5.450	0.004	0.017	0.000	0.000	0.000	14.044	8.000	5.996
	V3078	60.39	0.42	4.38	0.00	28.25	0.06	0.11	0.00	0.00	0.03	93.64	7.932	0.065	0.065	0.000	0.481	0.000	5.530	0.008	0.028	0.000	0.000	0.003	14.113	7.997	6.051
200R-2, 101–104	B2088	59.73	0.90	6.59	0.00	26.84	0.42	0.02	0.05	0.03	0.01	94.59	7.863	0.140	0.137	0.003	0.726	0.000	5.266	0.059	0.005	0.008	0.003	0.001	14.210	8.000	6.071
	B2089	60.51	0.80	6.25	0.02	26.20	0.36	0.02	0.03	0.00	0.12	94.31	7.957	0.124	0.043	0.082	0.687	0.002	5.135	0.051	0.005	0.005	0.000	0.012	14.104	8.000	5.979
	B2097	59.14	0.66	5.54	0.00	27.44	0.35	0.06	0.08	0.00	0.00	93.27	7.863	0.104	0.104	0.000	0.616	0.000	5.437	0.050	0.015	0.014	0.000	0.000	14.203	7.967	6.132
200R-3, 81–84	B5035	61.27	0.46	1.84	0.00	29.69	0.00	0.08	0.00	0.00	0.14	93.48	7.958	0.070	0.042	0.028	0.200	0.000	5.747	0.000	0.020	0.000	0.000	0.014	14.080	8.000	6.010
	B5036	61.87	0.32	2.36	0.00	29.08	0.00	0.05	0.00	0.00	0.00	93.68	8.022	0.049	0.000	0.049	0.256	0.000	5.620	0.000	0.013	0.000	0.000	0.000	14.008	8.022	5.937
210R-1, 56–60	B3111	62.72	0.13	2.07	0.06	30.09	0.03	0.05	0.01	0.00	0.07	95.23	8.001	0.020	0.000	0.020	0.221	0.006	5.720	0.004	0.012	0.002	0.000	0.007	14.013	8.001	5.992
	B3113	61.41	0.61	2.63	0.04	30.14	0.07	0.10	0.00	0.05	0.16	95.21	7.878	0.092	0.092	0.000	0.282	0.004	5.763	0.010	0.025	0.000	0.005	0.016	14.167	7.971	6.105
	B2052	60.46	1.17	3.01	0.01	30.17	0.00	0.12	0.02	0.04	0.10	95.10	7.788	0.178	0.178	0.000	0.324	0.001	5.792	0.000	0.030	0.003	0.004	0.010	14.308	7.966	6.165
228R-1, 58–60	B5114	60.84	0.22	1.59	0.00	29.62	0.07	0.03	0.00	0.03	0.16	92.56	7.973	0.034	0.027	0.007	0.174	0.000	5.785	0.010	0.008	0.000	0.003	0.017	14.037	8.000	6.003

Table 7. Representative epidote analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MnO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	Cr$_2$O$_3$	Cl	Total
193R-1, 44–46	P44	37.46	23.51	10.98	0.00	0.10	23.16	0.03	0.00	0.07	0.00	nd	95.31
209R-2, 108–111	B6043	38.51	23.24	12.75	0.18	0.20	23.31	0.02	0.00	0.01	0.00	nd	98.22
	B6045	38.08	22.52	13.49	0.09	0.20	23.31	0.00	0.01	0.00	0.06	nd	97.76
213R-1, 45–47	P65	38.13	21.82	12.70	0.08	0.88	21.76	0.03	0.00	0.10	0.00	nd	95.42
	P66	37.01	23.43	11.95	0.03	0.17	22.65	0.01	0.02	0.06	0.00	nd	95.30
214R-1, 67–70	B2193	39.53	21.75	12.18	0.00	0.53	23.09	0.09	0.09	0.04	0.00	0.02	97.32
	B2194	38.54	22.97	14.20	0.05	0.07	23.59	0.06	0.01	0.19	0.00	0.02	99.65
214R-1, 76–78	P3	37.63	24.41	11.71	0.14	0.09	23.77	0.00	0.00	0.06	0.02	nd	97.69
	P5	37.35	24.09	11.94	0.05	0.04	23.49	0.00	0.00	0.16	0.01	nd	97.08
216R-1, 7–10	A13	38.57	26.48	8.76	0.17	0.02	23.65	0.03	0.01	0.05	nd	nd	97.74
216R-1, 13–16	A15	37.69	21.17	14.30	0.10	0.00	23.45	0.00	0.02	0.22	nd	nd	96.95
	A16	37.91	23.81	10.59	0.11	0.04	23.76	0.00	0.00	0.07	nd	nd	96.29
216R-1, 58–60	B2033	35.66	22.51	11.21	0.15	0.27	21.87	0.00	0.00	0.00	0.04	0.03	91.59
	B2034	36.59	24.02	9.52	0.28	0.01	21.91	0.00	0.01	0.03	0.00	0.00	92.09
217R-1, 0–2	P77	38.23	25.55	10.43	0.15	0.02	23.40	0.02	0.00	0.13	0.00	nd	97.78
	P79	37.70	26.35	10.23	0.17	0.02	23.58	0.00	0.00	0.13	0.00	nd	98.01
226R-3, 5–9	B2075	39.99	21.30	12.51	0.04	1.96	22.20	0.03	0.00	0.09	0.00	0.00	98.08
	B2076	38.55	23.59	11.94	0.15	0.29	23.27	0.00	0.02	0.11	0.08	0.00	97.85

Note: Structural formulas are calculated on the basis of 12.5 oxygens.

Table 8. Representative prehnite analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MnO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	Cr$_2$O$_3$	Total
214R-2, 29–32	P25	42.55	20.75	3.19	0.00	0.60	24.66	0.05	0.25	0.01	0.05	92.11
	P27	42.56	20.80	3.06	0.06	0.24	25.57	0.04	0.00	0.05	0.00	92.38
216R-1, 7–10	A81	43.89	24.32	0.04	0.03	0.00	27.02	0.02	0.00	0.00	nd	95.32
	A82	43.51	23.58	0.06	0.00	0.00	24.91	0.08	0.00	0.00	nd	92.14
216R-1, 13–15	A85	42.60	23.43	1.98	0.03	1.13	23.42	0.00	0.01	0.02	nd	92.62
	A86	42.49	23.65	2.69	0.04	1.15	24.88	0.00	0.00	0.01	nd	94.91
216R-1, 58–60	P55	42.65	23.58	1.96	0.24	0.77	25.06	0.00	0.01	0.00	0.03	94.30
	P56	41.89	22.81	3.13	0.14	1.34	24.36	0.03	0.02	0.03	0.02	93.77
222R-1, 129–132	P82	41.87	22.53	2.53	0.06	1.77	23.93	0.04	0.00	0.00	0.00	92.73

Note: Structural formulas are calculated on the basis of 11 oxygens.

Table 9. Representative laumonite and heulandite analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	Occurrence	Mineral	SiO$_2$	Al$_2$O$_3$	FeO$_t$	MnO	MgO	CaO	Na$_2$O	K$_2$O	Ti$_2$O	Cr$_2$O$_3$	Total
187R-1, 57–60	V5117	ech	heul	59.97	17.41	0.17	0.00	0.02	8.46	0.05	0.06	0.02	0.00	86.16
	V5119	ech	heul	58.57	17.48	0.22	0.00	0.03	8.74	0.06	0.02	0.00	0.02	85.14
209R-2, 108–111	B6048	vug	heul	60.93	16.16	0.71	0.06	0.45	9.49	0.28	0.08	0.01	0.00	88.17
	B6050	vug	heul	60.45	15.91	1.49	0.00	1.47	8.72	0.23	0.05	0.03	0.00	88.35
214R-2, 29–32	P18	plagio	heul	56.28	15.36	0.96	0.03	0.74	8.94	0.18	0.03	0.02	0.05	82.57
	P21	plagio	heul	56.26	16.75	0.00	0.00	0.01	8.77	0.22	0.07	0.00	0.00	82.09
	P22	plagio	heul	57.30	16.69	0.00	0.00	0.01	8.65	0.15	0.10	0.00	0.04	82.96
187R-1, 57–60	V4106	ech	laum	55.71	21.62	0.30	0.05	0.02	10.77	0.10	0.06	0.01	0.00	88.64
	V4108	ech	laum	55.91	21.09	0.18	0.02	0.00	11.12	0.12	0.10	0.02	0.00	88.56
193R-1, 44–46	P45	plagio	laum	54.59	20.00	0.00	0.05	0.00	10.28	0.05	0.10	0.00	0.03	85.12
214R-1, 76–78	P6	vug	laum	52.72	21.41	0.00	0.00	0.00	11.93	0.06	0.00	0.00	0.00	86.14
	P7	vug	laum	52.31	21.55	0.02	0.07	0.00	11.98	0.05	0.00	0.00	0.10	86.10

Notes: laum = laumonite; heul = heulandite; ech = "échelon" crack-filling; plagio = partial plagioclase replacement; vug = vug composing the internal part of some alteration patches. Structural formulas are calculated on the basis of 72 oxygens for heulandite and 48 oxygens for laumonite.

permeability of the oceanic crust, is observed at various scales: at meter-scale, with intervals of poorly altered dolerites containing fresh olivine and interpreted as having experienced restricted exposure to hydrothermal fluids; at centimeter- or millimeter-scale, with alteration patches and extensively altered halos adjacent to veins.

2. One important alteration feature of Legs 137/140 is the formation of secondary clinopyroxene, before other secondary minerals. Two types of secondary clinopyroxene occur sporadically in Legs 137/140 dolerites: (1) green Na- and Ti-rich diopside-hedenbergite partly replaces igneous augite crosscut by an actinolite vein in two samples. By analogy with other occurrences of similar minerals in the pillow section, lithologic transition zone, and upper dike section of Hole 504B, we propose to interpret this secondary clinopyroxene, as well as melanite and fassaite from the pillow section, as resulting from an alteration by late magmatic fluids (deuteric alteration),

possibly mixed with small volumes of hydrothermal fluids, at temperatures of less than 500° to 600°C; (2) scarce colorless diopside, without anomalous Ti and Na concentrations, occurring in veinlets and patches, often associated with amphibole, is interpreted as having crystallized during hydrothermal alteration at minimum temperatures of 500°–700°C.

3. Amphibole is the most widespread and volumetrically abundant secondary mineral in the studied section. Many samples contain a continuous range of amphibole compositions, and there is a relation between the textural occurrence and the type of amphibole: actinolite prevails in veins, whereas actinolitic-hornblende and magnesio-hornblende prevail in the adjacent alteration halos. The lower sheeted dikes drilled during Legs 137/140 experienced higher temperature alteration in general than the shallower dikes, as evidenced by more prevalent actinolitic hornblende and, especially, abundant magnesio-

Table 7 (continued).

Si	Al	Fe₃	Mn	Mg	Ca	Na	K	Ti	Cr	Total	XFe₃
3.018	2.232	0.666	0.000	0.012	1.999	0.005	0.000	0.004	0.064	7.999	22.968
3.048	2.167	0.759	0.012	0.024	1.976	0.003	0.000	0.000	0.000	7.990	25.949
3.039	2.118	0.810	0.006	0.024	1.993	0.000	0.001	0.000	0.004	7.995	27.662
3.071	2.071	0.769	0.005	0.106	1.877	0.005	0.000	0.006	0.064	7.974	27.093
2.989	2.230	0.727	0.002	0.020	1.960	0.002	0.002	0.004	0.064	7.999	24.574
3.124	2.026	0.724	0.000	0.062	1.955	0.014	0.009	0.002	0.062	7.979	26.334
2.998	2.106	0.831	0.003	0.008	1.966	0.009	0.001	0.011	0.062	7.996	28.298
2.965	2.267	0.694	0.009	0.011	2.007	0.000	0.000	0.004	0.062	8.019	23.450
2.965	2.254	0.713	0.003	0.005	1.998	0.000	0.000	0.010	0.063	8.010	24.046
3.001	2.428	0.513	0.011	0.002	1.972	0.005	0.001	0.003	0.063	7.997	17.437
3.026	2.003	0.864	0.007	0.000	2.017	0.000	0.002	0.013	0.063	7.996	30.130
3.023	2.237	0.635	0.007	0.005	2.030	0.000	0.000	0.004	0.063	8.005	22.118
2.993	2.227	0.708	0.011	0.034	1.967	0.000	0.000	0.000	0.066	8.006	24.129
3.022	2.338	0.592	0.020	0.001	1.939	0.000	0.001	0.002	0.065	7.979	20.203
2.986	2.352	0.613	0.010	0.002	1.958	0.003	0.000	0.008	0.062	7.994	20.683
2.939	2.421	0.600	0.011	0.002	1.969	0.000	0.000	0.008	0.062	8.012	19.872
3.127	1.963	0.736	0.003	0.228	1.860	0.005	0.000	0.005	0.062	7.989	27.274
3.028	2.184	0.706	0.010	0.034	1.958	0.000	0.002	0.006	0.062	7.991	24.431

Table 8 (continued).

Si	Al	Fe₃	Mn	Mg	Ca	Na	K	Ti	Cr	Total	XFe₃
3.060	1.758	0.172	0.000	0.064	1.900	0.007	0.023	0.000	0.003	6.988	0.090
3.055	1.759	0.165	0.004	0.026	1.966	0.006	0.000	0.003	0.000	6.983	0.090
2.999	1.958	0.002	0.002	0.000	1.978	0.003	0.000	0.000	0.054	6.995	0.000
3.054	1.950	0.003	0.000	0.000	1.873	0.011	0.000	0.000	0.055	6.947	0.000
2.987	1.936	0.104	0.002	0.118	1.760	0.000	0.000	0.001	0.055	6.964	0.050
2.932	1.923	0.139	0.002	0.118	1.839	0.000	0.000	0.000	0.055	7.009	0.070
2.980	1.941	0.103	0.014	0.080	1.876	0.000	0.000	0.000	0.002	6.997	0.050
2.955	1.896	0.166	0.008	0.141	1.841	0.004	0.002	0.002	0.001	7.015	0.080
2.975	1.887	0.135	0.004	0.187	1.822	0.006	0.000	0.000	0.000	7.016	0.070

Table 9 (continued).

Si	Al	Fe₃	Mn	Mg	Ca	Na	K	Ti	Cr	Total
26.963	9.225	0.064	0.000	0.013	4.075	0.044	0.034	0.007	0.000	40.425
26.721	9.398	0.084	0.000	0.020	4.272	0.053	0.012	0.000	0.007	40.567
27.123	8.478	0.026	0.023	0.299	4.526	0.242	0.045	0.003	0.000	40.765
27.130	8.632	0.078	0.023	0.106	4.373	0.190	0.040	0.000	0.039	40.611
26.676	8.580	0.380	0.012	0.523	4.540	0.165	0.018	0.007	0.019	40.920
26.685	9.363	0.000	0.000	0.007	4.457	0.202	0.042	0.000	0.000	40.756
26.848	9.216	0.000	0.004	0.014	4.342	0.136	0.060	0.000	0.015	40.635
16.530	7.560	0.074	0.013	0.009	3.424	0.058	0.023	0.002	0.000	27.691
16.621	7.388	0.045	0.005	0.000	3.542	0.069	0.038	0.004	0.000	27.712
16.825	7.264	0.000	0.013	0.000	3.395	0.030	0.039	0.000	0.007	27.574
16.208	7.757	0.000	0.000	0.000	3.930	0.036	0.000	0.000	0.000	27.931
16.116	7.824	0.005	0.018	0.000	3.954	0.030	0.000	0.000	0.024	27.972

chlorite layers than that at the cores of the pseudomorphs. In the intervals where relict olivine is present and where talc replaces olivine, chlorite-smectites contain relatively lower proportions of chlorite layers (1700–1820, 1905–1938, and 1980–1985 mbsf). Such variations can be explained by differences in temperature of reaction (ranging from 60° to 320°C, calculated using Cathelineau geothermometer), or by variations in water-rock ratio and extent of reaction of the rocks.

6. The distribution of Al^{IV} and TiO$_2$ of amphiboles with depth is very irregular and reaches maxima at 1630 and 1820 mbsf, implying higher temperatures of crystallization. The geothermometry data obtained from chlorite-smectite indicate that three depth levels (1630–1650, 1835, and 1980 mbsf) probably experienced higher temperature of alteration than the other depth levels. At 1980 mbsf, Al^{IV} in amphiboles also reaches a maximum. We know that the highest Al^{IV} and Ti contents are mostly represented by amphibole, which crystallizes in the halos and in the host rock, and are interpreted as being prior to chlorite-smectite. We propose that in these three depth zones, the temperature was higher than elsewhere in the Legs 137/140 section during the two first stages of alteration.

7. Spatial relationships and geothermometric arguments allow us to propose the following sequence of alteration:

Stage 1a, high temperature (less than 500° to 600°C). It only has a replacement effect, with Na, Ti-rich diopside very locally replacing primary augite along veins. This should be a deuteric or mixed deuteric-hydrothermal stage.

Stage 1b, high temperature (500°–700°C). Very small amounts of secondary diopside, without anomalous Na or Ti, crystallize locally in veinlets and patches, possibly prior to Stage 1c, suggesting a water/rock ratio low and then higher.

Stage 1c, high temperature (400°–500°C). Fills open cracks and mainly creates alteration halos around veins and patches. It mainly has a replacement effect, with anorthite replacing plagioclase rim in alteration halos, and hornblende replacing augite, extensively in al-

hornblendes. The lack of Cl-rich amphiboles may indicate that unusually briny hydrothermal fluids did not develop in the lower sheeted dikes during water-rock interaction.

4. One major new discovery in Hole 504B is the presence of, in some extensively altered vein halos, hydrothermal plagioclase (An$_{80-95}$) that is more calcic than the associated igneous plagioclase (An$_{65-89}$). This secondary plagioclase has been recognized here for the first time in the oceanic crust. The appearance of calcic plagioclase downhole correlates roughly with increases in, but not the first appearance of, magnesio-hornblende. We interpret this hydrothermal anorthite-bytownite, in association with magnesio-hornblende, as being formed in a reaction zone similar to that envisioned for the source of black smoker fluids, from high-temperature (>400°–500°C), Ca-enriched fluids.

5. Mixed-layer chlorite-smectite exhibit several types of variation in the percentage of chlorite layers present. Chlorite-smectite in veins contains a greater proportion of chlorite layers than that replacing olivine in the host-rock of the same sample, and chlorite-smectite in the rims of olivine pseudomorphs contains a greater percentage of

teration halos and along the vein edges in the multiply opened veins, and less extensively out of the halos. The low permeability zones did not react to these relatively small amounts of hot fluids.

Stage 2, lower temperature (250°–320°C). Actinolite and minor chlorite form in the central part of the veins, albite partly replaces primary and secondary An-rich plagioclase, chlorite and chlorite-smectite and/or talc (in low permeability zones) replace olivine in the host-rock, and various and abundant amphiboles replace igneous clinopyroxene. The temperature possibly decreased during this stage, leading to the formation of more smectitic clay-minerals.

Stage 3, relatively high temperature (310°–320°C). Epidote and quartz form in veins and vugs, probably from more evolved fluids. This stage of alteration affects only very slightly the host rock, epidote partially replacing plagioclase in rare instances.

Stage 4, low temperature. Anhydrite crystallizes, probably directly from heated seawater.

Stage 5, low temperature (250°C). Laumontite and prehnite form.

8. Several lines of evidence suggest that most of the hydrothermal fluids that altered the sheeted dikes at Hole 504B were seawater derived: (1) fluid inclusions in secondary plagioclase have seawater-like salinities; (2) isotopic signature of altered dolerites suggests seawater contamination; and (3) the high volume of hydrous secondary minerals.

9. Most of the sheeted dike alteration resulted from non-focused, pervasive fluid-rock interaction as opposed to focused, high-temperature, high-W/R discharge alteration. The lower section of dikes of Hole 504B probably represents lower crustal regions that have never been zones of concentrated upwelling of hydrothermal fluids or black smoker vents.

ACKNOWLEDGMENTS

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Table 10. Representative titanite analyses, Hole 504B, Legs 137/140.

Core, section, interval (cm)	Analysis	SiO₂	Al₂O₃	Fe₂O₃ₜ	MnO	MgO	CaO	Na₂O	K₂O	TiO₂	Cr₂O₃	Cl	ZnO	Total
173R-1, 77–79	B2179	30.18	1.42	0.75	0.00	0.00	28.58	0.17	0.00	37.95	0.00	0.03	0.00	99.05
	B2180	30.36	1.51	0.84	0.02	0.01	29.05	0.15	0.19	37.31	0.00	0.12	0.00	99.44
177R-1, 11–15	B2116	33.67	1.90	3.83	0.02	1.97	26.98	0.07	0.01	32.14	0.02	0.03	0.00	100.61
	B2117	31.37	2.69	1.39	0.10	0.00	28.60	0.02	0.02	35.49	0.15	0.02	0.00	99.83
	B2121	30.72	1.54	1.04	0.03	0.04	29.64	0.02	0.00	37.39	0.00	0.00	0.13	100.42
237R-1, 24–26	B3007	31.30	3.87	1.93	0.01	0.00	28.81	0.00	0.00	32.84	0.06	0.03	0.00	98.82

Note: Structural formulas are calculated for 20 oxygens.

Table 10 (continued).

Si	Ti	Al	Fe³⁺	Cr	Mn	Zn	Mg	Ca	Na	K	Total
3.984	3.767	0.221	0.068	0.000	0.000	0.000	0.000	4.042	0.044	0.000	12.126
4.000	3.697	0.234	0.075	0.000	0.002	0.000	0.002	4.101	0.038	0.032	12.183
4.348	3.121	0.289	0.335	0.002	0.002	0.000	0.379	3.733	0.018	0.002	12.228
4.095	3.484	0.414	0.123	0.015	0.011	0.000	0.000	4.000	0.005	0.003	12.150
4.007	3.668	0.237	0.092	0.000	0.003	0.013	0.008	4.143	0.005	0.000	12.163
4.125	3.255	0.601	0.173	0.006	0.001	0.000	0.000	4.068	0.000	0.000	12.230

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Plate 1. **1.** Secondary Na-, Ti-diopside (d) replacing igneous augite (a) in contact with an actinolite (ac) + titanite (ti) vein in Sample 137-504B-180M-1, 74–78 cm (Piece 7) (plane polarized light). pl = plagioclase. Scale bar is 0.2 mm. **2.** Actinolite vein, hornblende in adjacent alteration halo in Sample 140-504B-197R-1, 100–102 cm (Piece 22) (plane polarized light). Scale bar is 0.5 mm.

Plate 2. **1.** Photomicrograph of dolerite from a vein halo, Sample 140-504B-205R-1, 13–16 cm (Piece 1), taken with a cathodoluminescence microscope (17 KeV accelerating voltage, 0.5 mA beam current). The field of view is from a well-developed alteration halo along an amphibole vein. Igneous plagioclase laths luminesce blue-gray and possess thick incomplete rims of greenish hydrothermal calcic plagioclase. Interstitial amphibole is nonluminescent. Electron microprobe analysis spots are labeled and are given in Table 4. Plagioclase cores are An_{74-77}, whereas the rims are An_{89-94}. Late-stage crosscutting veinlets of nonluminescent albite are An_{11}. Scale bar is 0.5 mm.   **2.** Olivine phenocryst replaced by chlorite (Chl) + magnetite (Ma) at the rim (analyses B3104, B5009, B5014; Table 5), mixed-layer chlorite-smectite (C/Sm) in the core (analyses B3103, B5025, B5026; Table 5) in Sample 140-504B-208R-2, 76–81 cm (Piece 13) (plane polarized light). Scale bar is 0.2 mm.