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5. STABLE AND STRONTIUM ISOTOPIC PROFILES THROUGH HYDROTHERMALLY ALTERED UPPER OCEANIC CRUST, HOLE 504B[1]

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ABSTRACT

Leg 148 penetrated 111 m farther into Hole 504B, to a total depth of 2111 meters below seafloor (mbsf), and recovered diabase dikes similar to the immediately overlying rocks. Secondary mineralogy and whole-rock oxygen and strontium isotopic compositions were determined for samples from Leg 148. In addition, strontium isotopic analyses were performed on previously recovered samples of the lower dikes (1550–2000 mbsf). Trends observed in the lower dikes (1550–2000 mbsf) continue in the Leg 148 section (2000–2111 mbsf). These include the local presence of magnesiohornblende and secondary calcic plagioclase and high Ti contents of amphiboles. Cu, Zn, and S contents of the more altered rocks are low, and whole-rock $\delta^{18}O$ values of 3.3‰–4.5‰ continue the trend of decreasing $\delta^{18}O$ with depth. These trends reflect alteration at higher temperatures (>350°C) and greater extents of recrystallization than in the upper dikes. All of the data for the new Leg 148 section are consistent with the rocks being a continuation of a subsurface reaction zone, where metals and sulfur are leached from the crust by hydrothermal fluids and transported to form metal sulfide mineralizations on or within the crust or vent into seawater.

Sr contents of the lower sheeted dikes (1550–2111 mbsf) are generally 48–62 ppm, and whole-rock $^{87}Sr/^{86}Sr$ ratios range from 0.70265 to 0.70304, only slightly elevated relative to fresh MORB values. The rocks were altered by seawater-derived hydrothermal fluids, with little change in the Sr concentrations of the rocks. Although amphibole is the most abundant secondary phase, the Sr isotopic composition of the rocks is probably dominated by the abundance of secondary plagioclase. The $^{87}Sr/^{86}Sr$ ratios of hydrothermal fluids were higher than measured in variably recrystallized (10%–80%) whole rocks. The seawater component of hydrothermal fluids increased through time, as documented by $^{87}Sr/^{86}Sr$ ratios of 0.7028–0.7034 for amphibole and chlorite, to 0.7035–0.7038 for vein epidotes. The latter values record the composition of upwelling black smoker-type end-member hydrothermal fluids at Site 504.

The low $^{87}Sr/^{86}Sr$ ratios for the lower dikes differ from the uniformly high ratios of the thoroughly recrystallized sheeted dikes from the Troodos ophiolite. The oceanic dikes interacted with much smaller volumes of seawater than the ophiolitic rocks and apparently to a lesser extent. These differences are in some way related to the contrasting tectonic setting, mineralogy, and chemical composition of ophiolites compared to in situ ocean crust.

INTRODUCTION

Ocean Drilling Program (ODP) Hole 504B in the eastern Pacific is the deepest scientific drill hole into the ocean crust, with penetration to 2111 m below seafloor (mbsf) (1836.5 m sub-basement) over the course of seven drilling legs. It is the only hole to penetrate through the volcanic section, altered at low temperatures, into the underlying hydrothermally altered sheeted dike complex. The site has become a reference section for the petrology, geochemistry, hydrothermal alteration, and magnetic and physical properties of the upper oceanic crust (Anderson et al., 1982; Becker et al., 1989; Dick, Erzinger, Stokking, et al., 1991; Alt, Kinoshita, Stokking et al., 1993).

Hole 504B is located in 5.9-m.y.-old crust, 200 km south of the intermediate spreading-rate Costa Rica Rift (Fig. 1). Before Leg 148, Hole 504B had penetrated 274.5 m of sediments (Fig. 2), a 571.5-m volcanic section, a 209-m transition zone, and 945.4 m of sheeted dikes. Core recovery averaged 30% in the volcanic section, 25% in the transition zone, and 14% in the sheeted dikes. During January–March 1993, drilling on Leg 148 deepened Hole 504B by 110.6 m (from 2000.4 to 2111.0 mbsf; Fig. 2) (Alt, Kinoshita, Stokking, et al., 1993). Core recovery averaged 14% and recovered diabase dikes, apparently similar to the immediately overlying dikes (Alt, Kinoshita, Stokking, et al., 1993). This paper presents secondary mineralogy and oxygen and strontium isotopic analyses of whole rocks and secondary phases for rocks from Hole 504B sampled on Leg 148, plus additional Sr isotope analyses of the lower sheeted dikes recovered from the hole during Legs 137 and 140. The objectives are to constrain the conditions of alteration, as well as hydrothermal fluid compositions and previous reaction histories. Of particular interest are the controls on the Sr isotopic compositions of altered rocks and hydrothermal fluids. Also addressed are whether chemical, isotopic, and mineralogical trends identified in the lower dikes (e.g., increasing Ti and Al in amphibole, decreased whole-rock S, Cu, and Zn contents, and decreased $\delta^{18}O$ values; Alt et al., 1989b, 1995; Zuleger et al., 1995; Laverne et al., 1995), which are attributed to increasing alteration temperatures in the hydrothermal "reaction zone," continue in the Leg 148 section. Whole-rock chemical analyses of the same samples analyzed in this paper are presented elsewhere (Bach et al., this volume), and more extensive and detailed mineralogical data are given by Vanko et al. (this volume).

SITE 504

The basement rocks sampled in Hole 504B comprise aphyric to highly phyric tholeiitic basalts, having moderately evolved mid-

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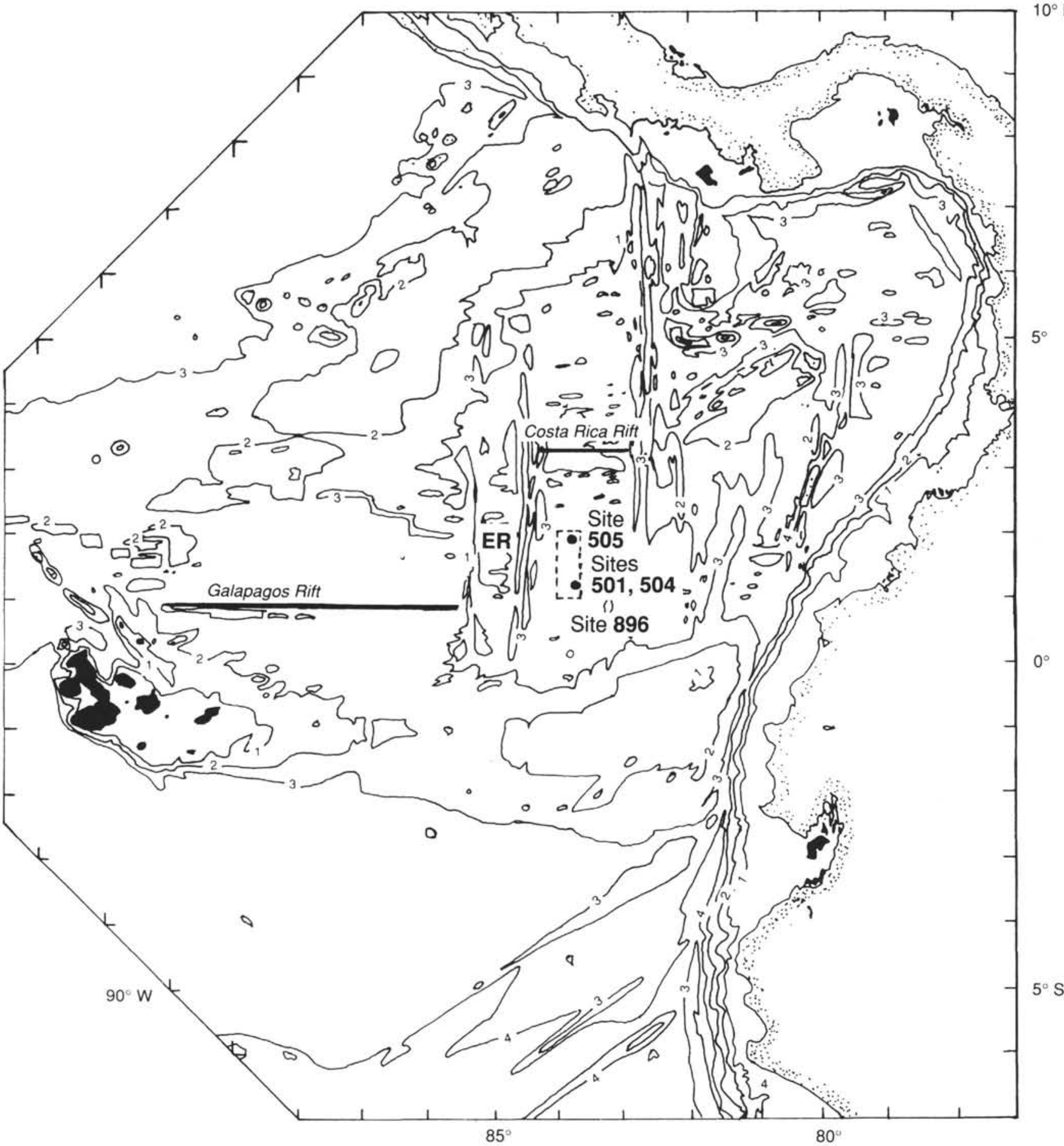

Figure 1. Location of DSDP Sites 501 and 505, DSDP/ODP Site 504, and ODP Site 896 south of the Costa Rica Rift in the eastern equatorial Pacific (after Hobart et al., 1985).

ocean ridge basalt (MORB) compositions with Mg numbers mostly in the range from 0.63 to 0.74. The rocks are unusually depleted in incompatible elements (e.g., TiO_2, Nb, and Zr), but have incompatible element ratios comparable to normal MORB. The basalts have been interpreted as being either very primitive (Emmermann, 1985; Natland et al., 1983), or the result of multi-stage melting of a normal MORB mantle source followed by moderate extents of crystal fractionation (Autio and Rhodes, 1983; Autio et al., 1989; Kempton et al., 1985). The exceptional uniformity in composition of the basalts has been interpreted to indicate the presence of a steady-state magma chamber beneath the rift axis (Natland et al., 1983). Three units (two volcanic and one dike), which comprise less than 2% of the core, have enriched- or transitional-type MORB chemistries (Autio and Rhodes, 1983; Emmermann, 1985). A separate mantle source has been suggested for these rocks (Emmermann, 1985), but their origin remains problematic.

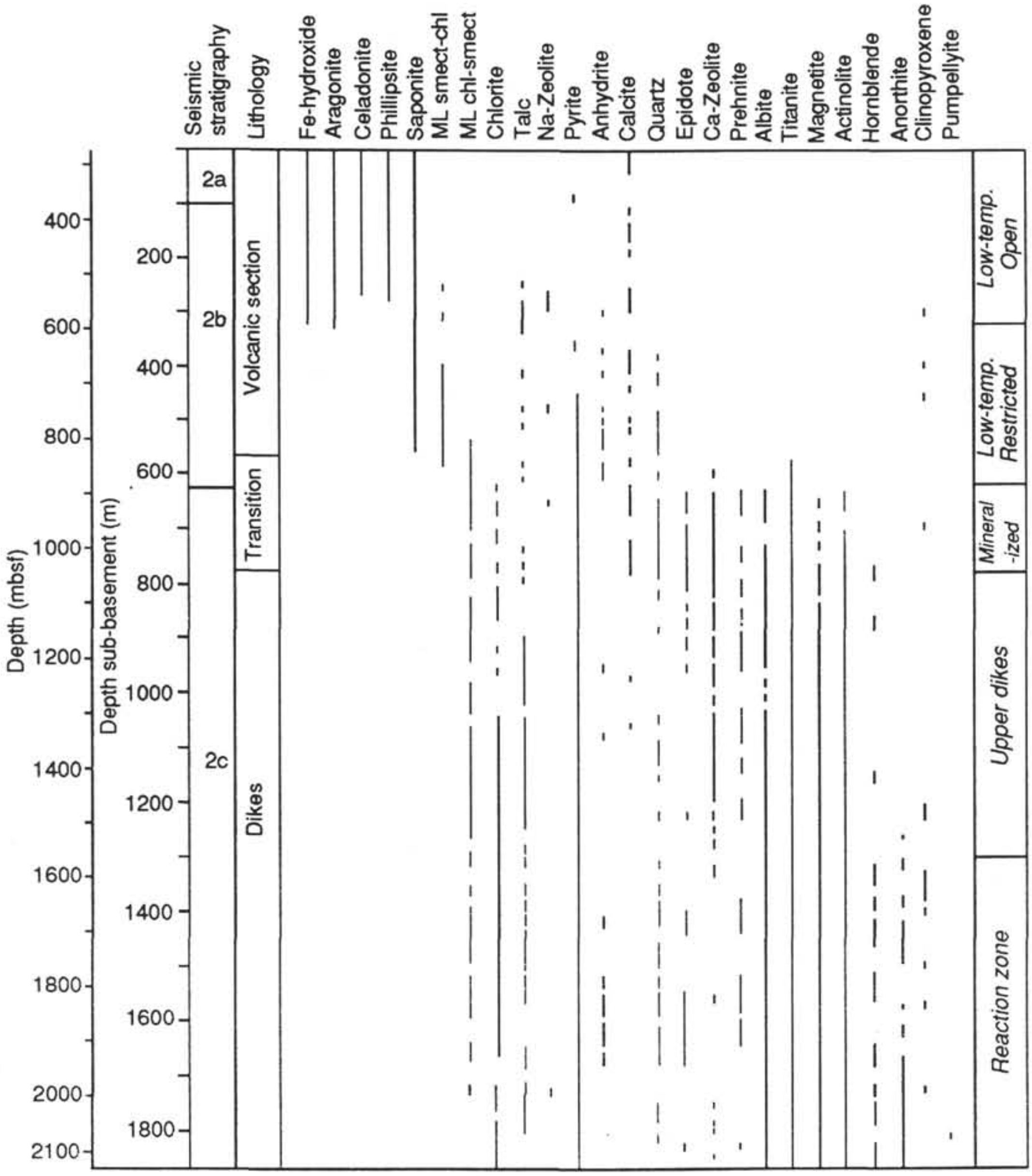

Figure 2. Lithostratigraphy of Hole 504B, showing the distribution of secondary minerals with depth in the core.

Hole 504B can be divided into five alteration zones (Fig. 2; Alt et al., 1986a, 1995).

1. The upper 320 m of the volcanic section (274.5–594.5 mbsf) was affected by oxidizing alteration at low temperatures (<100°C), as the result of open circulation of seawater through the highly permeable upper extrusives.
2. The lower half of the volcanic section (594.5–898.5 mbsf) was affected by low-temperature (<150°C), reducing alteration with more restricted flow of seawater.
3. Rocks in the transition zone from the volcanic section to sheeted dikes are intensely hydrothermally altered and mineralized, and a stockwork-like sulfide mineralization occurs from 910 to 928 mbsf. These rocks were altered in a subsurface mixing zone, where 250°–350°C hydrothermal fluids upwelling through the dikes mixed with cooler seawater solutions circulating in the overlying volcanic section.
4. The upper dikes (1055–1600 mbsf) were hydrothermally altered to varying degrees under sub-greenschist to greenschist and superimposed zeolite facies conditions.
5. The lower dike section or reaction zone (1600–2111 mbsf) is characterized by higher alteration temperatures approaching amphibolite facies conditions, greater intensity of alteration, and depletions of base metals and sulfur (Alt et al., 1995; Laverne et al., 1995; Zuleger et al., 1995).

The sequence of hydrothermal alteration in the transition zone and upper half of the dike section can be summarized in four stages (Alt et al., 1986a, 1989b). First, chlorite and actinolitic amphibole formed in veins and greenschist minerals (actinolitic amphibole, albite-oligoclase, chlorite, talc, and titanite) formed in the groundmass during axial hydrothermal alteration at temperatures of ~250°–350°C. Second, quartz, epidote and sulfides formed in veins, and the sulfide mineralization formed in the transition zone. Later, as the crust moved off-axis into a recharge zone, penetration of seawater into still-warm rocks resulted in precipitation of anhydrite in cracks and local replacement of plagioclase by anhydrite. Finally, zeolites formed in fractures and rocks during later off-axis alteration at lower temperatures (less than about 150°–250°C).

Important changes occur with depth in the dikes (Alt et al., 1989b, 1995; Laverne et al., 1995; Vanko et al., this volume). The replacement of primary igneous plagioclase by sodic plagioclase (albite-oligoclase) in the upper dikes decreases with depth, and secondary calcic plagioclase (An$_{75}$–An$_{93}$) and minor secondary clinopyroxene appear in the lower dikes (Fig. 2). The abundance of zeolites decreases in the lower dikes and anhydrite is present within the bulk rock, rather than fracture fillings as in the upper dikes. Both the abundance of amphibole and the Ti and Al contents of amphibole increase with depth (Fig. 3), with compositions changing from mainly actinolite in the upper dikes to common magnesiohornblende in the lower dikes. The Zn, Cu, and S contents of the rocks decrease below 1600 mbsf (Fig. 4), and δ^{18}O values progressively decrease throughout the dikes (Fig. 5; Alt et al., 1986a, 1989b, 1995; Zuleger et al., 1995; Laverne et al., 1995). These mineralogical and chemical changes generally reflect higher alteration temperatures and greater extents of reaction with depth, in conditions approaching the amphibolite facies. The lower dikes underwent an early high-temperature alteration stage (>400°C), which resulted in the formation of secondary calcic plagioclase and hornblende, mainly in localized centimeter-scale alteration zones. This stage preceded the alteration sequence outlined above for the upper dikes, and alteration at temperatures >350°C was more pervasive and/or persistent in the lower than in the upper dikes (Laverne et al., 1995; Alt et al., 1995; Vanko et al., this volume). Subsequent alteration stages were similar to those in the upper dikes, with greenschist minerals in veins and rocks cut by later quartz plus epidote veins. Anhydrite is a minor late phase in veins and rocks, and only very minor later zeolites are present in the lower dikes. The present temperature in Hole 504B increases with depth to approximately 180°C at the bottom of the hole. It is unlikely that the rocks in the lower 500 m have ever been cooler than the currently measured 155°–180°C over this depth interval.

Hole 504B has been logged with an extensive suite of downhole tools during several legs, providing important information about the physical properties of the crust. The sonic data indicate a thin Layer 2A (Fig. 2), consisting of highly porous and permeable volcanic rocks in the upper 100–200 m. Layer 2B comprises the lower 500 m of volcanic rocks, in which the original porosity has been mostly sealed by secondary minerals. The physical properties change significantly across the transition from volcanic rocks to sheeted dikes: the sonic velocities and resistivity increase sharply whereas bulk permeability and porosity drop by orders of magnitude (Anderson et al., 1982). Porosities and thermal conductivities decrease with depth in the dikes, and seismic velocity and resistivity gradients flatten out at about 1500 mbsf. Detrick et al. (1994) interpreted these changes as marking the transition from seismic Layer 2 to Layer 3 at Site 504.

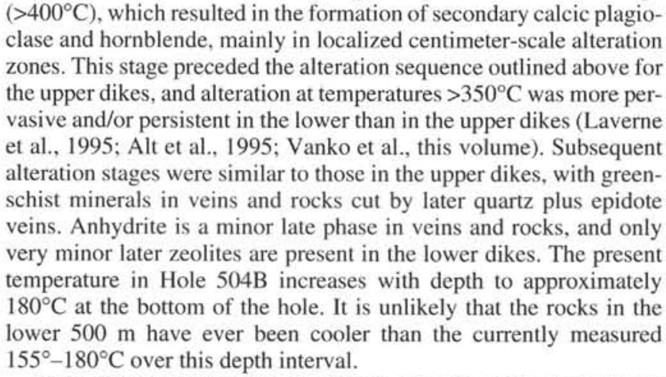

Figure 3. Variation in amphibole abundance and composition with depth in the sheeted dikes of Hole 504B. Magnesiohornblende becomes common and Ti contents are generally higher below about 1550 mbsf, consistent with generally higher temperatures of alteration in the lower dikes. Hblde = hornblende. Data from this work and Alt et al. (1985, 1986a, 1986b, 1995).

Drilling in Hole 504B was halted in a suspected fault zone at 2111 mbsf, where the drilling rate increased in the presumably pulverized rock, and in which the drill string became stuck, preventing further penetration (Alt, Kinoshita, Stokking, et al., 1993). Unfortunately, no material from the fault zone was recovered nor was it possible to make any logging measurements in this interval, so the nature of the material in the fault zone remains unknown. What lies on the other side of the fault also remains unanswered. On the basis of the common occurrence of décollements separating the sheeted dikes and uppermost plutonic rocks in ophiolites (e.g., Lemithou-Kakopetria Detachment in the Troodos ophiolite; Varga, 1991), it may be that this fault marks the boundary between sheeted dikes and underlying gabbros (Alt, Kinoshita, Stokking, et al., 1993).

METHODS

The samples studied are representative of the various types of material recovered from Hole 504B during Leg 148. In addition to a selection of least-altered samples, several pairs of highly altered zones plus associated host diabase were investigated petrographically and analyzed for their oxygen and strontium isotopic compositions. Because of the lack of strontium isotopic data from the Leg 137 and 140 sections of Hole 504B (1550–2000 mbsf), we also determined Sr isotopic compositions of rocks from this interval.These samples have been previously characterized for their mineralogy, oxygen, and sulfur isotopic and major and trace element compositions (Alt et al., 1995; Zuleger et al., 1995).

The degree of alteration, defined as the modal abundance of secondary minerals, was estimated petrographically. The estimates agree within 5%–10% of modal analyses by point counting. Secondary minerals were studied in transmitted and reflected light, and identifications were aided by energy-dispersive X-ray analyses. Chemical compositions of secondary minerals were determined by electron microprobe (Cameca CAMEBAX MBX-microbeam with four wavelength-dispersive spectrometers) using a 10 nA beam current and 15 kV accelerating potential rastered over a 6 × 6 µm area. Some secondary mineral chemistry is discussed in this paper, but more detailed and comprehensive analyses are given elsewhere (Vanko et al., this volume).

Whole-rock samples were selected to be representative of the different alteration types, with more intensely altered zones separated from the dark gray host rock by sawing where possible (Table 1). Samples for isotopic analysis were pulverized in a tungsten carbide shatter-box. Oxygen was extracted from whole-rock powders and from minerals separated from veins by reaction with ClF$_3$ and converted to CO$_2$ gas using the techniques of Clayton and Mayeda (1963). Oxygen isotope ratios were then analyzed on a Finnigan Delta-S mass spectrometer. Results are reported as δ notation relative to standard mean ocean water (SMOW; Craig, 1961), where $\delta^{18}O(‰) = 10^3 \times \{[(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{SMOW}]/(^{18}O/^{16}O)_{SMOW}\}$.

Repeated extractions and measurements of samples and standards were reproducible within ±0.2‰. Sulfur was extracted from whole-rock powders in a stepwise process to obtain acid-soluble sulfide (pyrrhotite, pentlandite), pyrite plus chalcopyrite sulfur, and soluble sulfate sulfur (Alt et al., 1995).

Strontium isotopic compositions and rubidium and strontium concentrations were determined by isotope dilution and thermal ioniza-

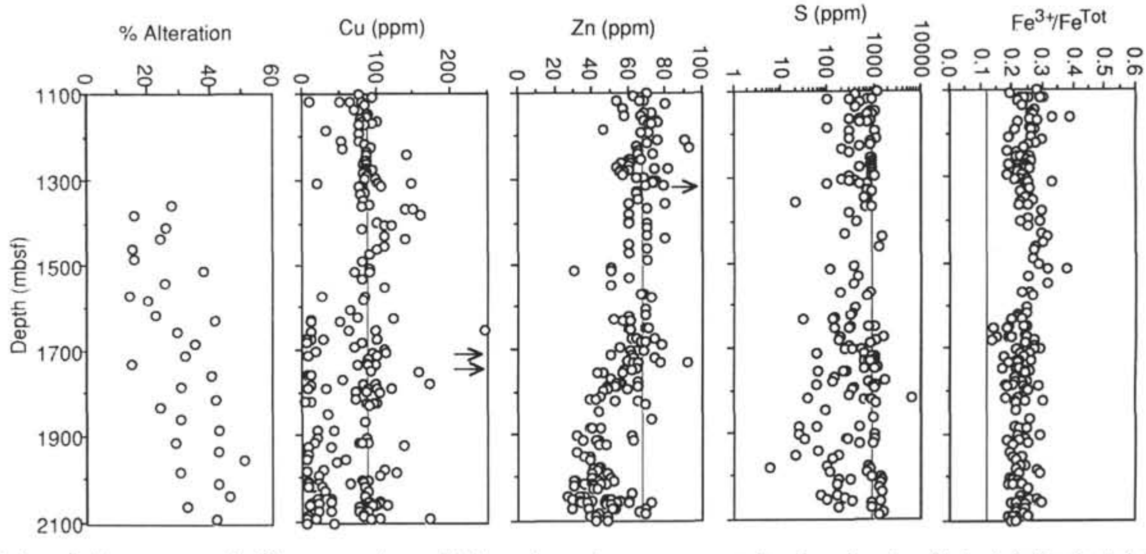

Figure 4. Whole-rock zinc, copper, and sulfur contents, iron oxidation ratios, and average percent alteration of rocks with depth in the sheeted dikes of Hole 504B. Note the decrease in Zn content in the lower dikes from approximately 1600 mbsf downward. Cu exhibits a bimodal distribution in the lower dikes, with the more altered rocks more depleted in Cu. Sulfur (note logarithmic scale) exhibits increasing scatter to low S contents with depth. The Fe^{3+}/Fe^{Tot} ratio is fairly constant with depth in the lower dikes (≈0.25), but is slightly elevated above the initial igneous value (0.12, vertical line), which indicates a moderate pervasive oxidation. The average secondary mineral proportions were calculated per 25 m depth from shipboard and published point counting and petrographic estimates (Becker et al., 1989; Dick, Erzinger, Stokking, et al., 1992; Alt, Kinoshita, Stokking, et al., 1993; Alt et al., 1995; Zuleger et al., 1995). Vertical lines indicate mean igneous concentrations. Arrows indicate samples that plot off scale.

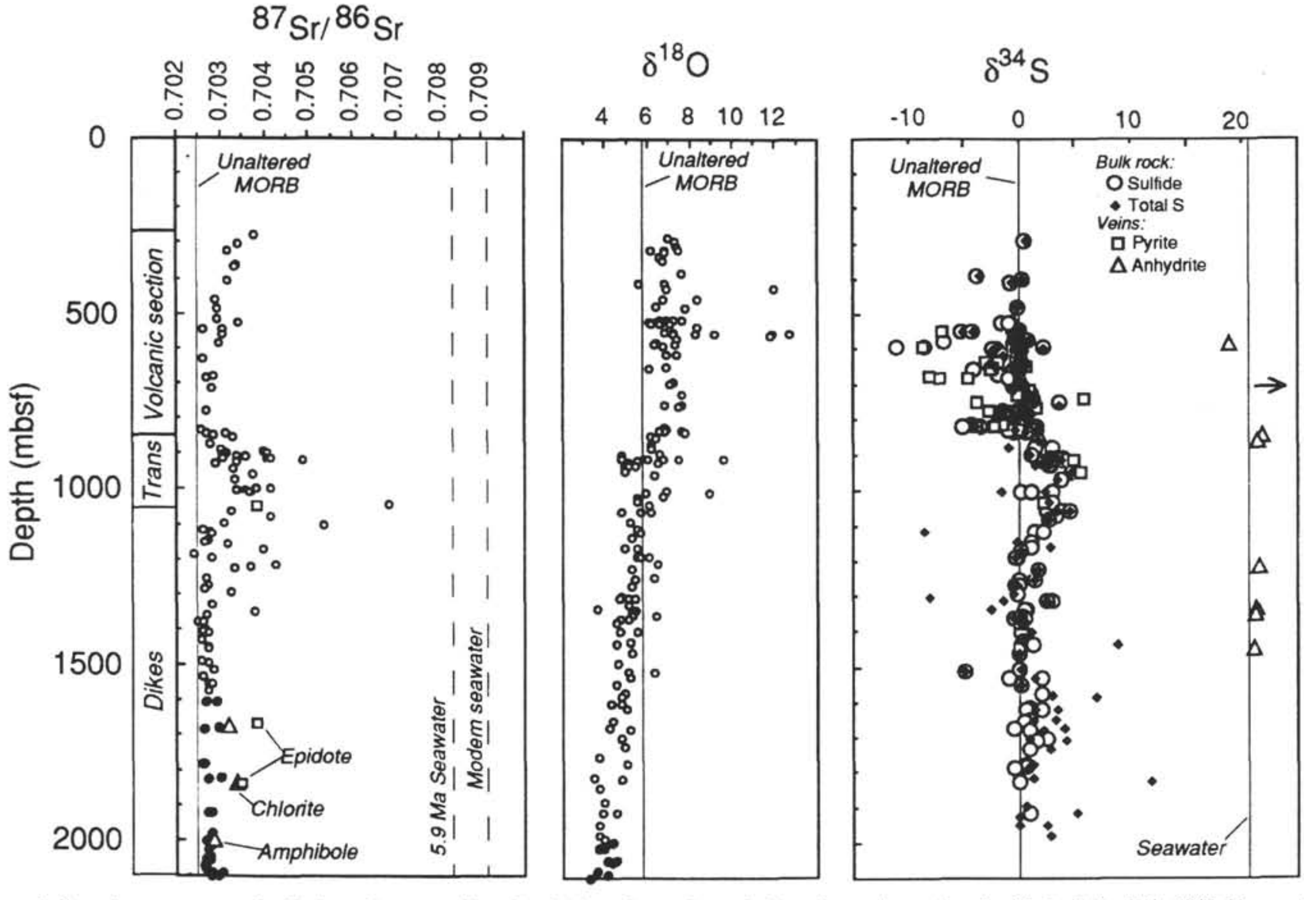

Figure 5. Strontium, oxygen, and sulfur isotopic compositions for whole-rock samples and selected secondary minerals with depth for Hole 504B. Trans = transition zone. Strontium data from Table 1 (whole rocks = solid circles; secondary minerals are labeled) and various sources (Barrett and Friedrichsen, 1982, 1987; Barrett, 1983; Hart and Mottl, 1983; Friedrichsen, 1985; Staudigel and Hart, 1985; Kawahata et al., 1987; Kusakabe et al., 1989; Shimizu et al., 1989). Oxygen data from Table 1 (solid circles), Alt et al. (1986b, 1989b, 1995), and Nesbitt et al. (1987). S data from Alt et al. (1989a, 1995), Zuleger et al. (1995), and Bach et al. (this volume).

Table 1. Oxygen and strontium isotopic compositions, strontium and rubidium concentrations, and percent alteration for Leg 137, 140, and 148 samples from Hole 504B.

Core, section interval (cm)	Depth (mbsf)	Unit	Type	Alteration (%)	$\delta^{18}O$ (‰)	$^{87}Sr/^{86}Sr$	±2σ	Sr (ppm)	Rb (ppm)
137-504B-									
173R-1, 134–137 (Piece 13)	1575.12	194	Dark	15	4.9	0.702737	±0.000020	49	0.062
177R-1, 11–14 (Piece 4A)	1605.81	201	Dark	20	4.3	0.702919	±0.000020	48	0.148
177R-1, 11–14 (Piece 4B)	1605.81	201	Light	50	4.8	0.702687	±0.000021	45	0.059
140-504B-									
192R-1, 13–15 (Piece 4)	1672.10	218	Epidote	100	5.1	0.703845	±0.000020	NA	NA
192R-1, 13–15 (Piece 4)	1672.10	218	Amph	100	NA	0.703156	±0.000014	NA	NA
193R-1, 22–24 (Piece 7)	1676.73	220	Patch	60	4.2	0.702977	±0.000018	60	0.415
194R-1, 36–40 (Piece 7)	1680.85	220	Dark	20	5.2	0.702651	±0.000014	48	0.417
208R-1, 88–91(Piece 19A)	1780.73	239	Halo	35	5.0	0.702651	±0.000018	53	0.072
208R-1, 110–116 (Piece 23)	1781.41	239	Dark	18	5.0	0.702623	±0.000021	57	0.080
214R-1, 73–76 (Piece 8)	1819.75	244	Patch	90	3.5	0.702998	±0.000014	49	0.130
215R-1, 59–63 (Piece 15)	1827.12	244	Dark	15	4.8	0.702708	±0.000017	53	0.043
216R-1, 70–75 (Piece 15A)	1833.00	245	Chlorite	100	n.a	0.703452	±0.000017	NA	NA
217R-1, 0–5 (Piece 1)	1837.50	245	Epidote	100	NA	0.703408	±0.000017	NA	NA
225R-2, 68–72 (Piece 13A)	1919.52	260	Dark	20	4.5	0.702746	±0.000014	55	0.046
225R-2, 68–72 (Piece 13B)	1919.52	260	Halo	60	3.9	0.702825	±0.000014	52	0.032
236R-1, 26–28 (Piece 5B)	1981.78	269	Patch	60	3.7	0.702826	±0.000018	59	0.098
238R-1, 8–9 (Piece 2)	1994.87	269	Dark	25	4.0	0.702751	±0.000020	53	0.046
148-504B-									
239R-1, 45–51 (Piece 14)	2000.85	270	Dark	30	4.4	0.702681	±0.000014	62	0.066
239R-1, 45–51 (Piece 14)	2000.85	270	Halo	70	3.7	0.702762	±0.000018	89	0.058
239R-1, 45–51 (Piece 14)	2000.85	270	Amph	100	NA	0.702808	±0.000013	14	0.098
240R-1, 95–95 (Piece 22)	2007.80	274	Patch	70	NA	0.702798	±0.000015	59	0.057
241R-1, 11–15 (Piece 4)	2016.61	276	Dark	40	NA	0.702824	±0.000013	60	0.042
241R-1, 42–46 (Piece 9)	2017.00	276	Dark	30	4.0	0.702773	±0.000020	55	0.032
241R-1, 95–98 (Piece 19)	2017.45	276	Halo	65	3.7	0.702772	±0.000014	54	0.029
242R-1, 0–5 (Piece 1)	2025.90	276	Patch	60	NA	0.702735	±0.000015	53	0.059
245R-1, 48–51 (Piece 16)	2043.31	281	Dark	50	NA	0.702770	±0.000014	61	0.147
246R-1, 8–11 (Piece 4)	2052.29	283	Halo	30	NA	0.702744	±0.000014	58	0.050
246R-1, 26–30 (Piece 9)	2052.50	283	Patch	40	4.5	0.702667	±0.000014	61	0.055
246R-1, 46–50 (Piece 14)	2052.66	283	Dark	25	NA	0.702685	±0.000014	55	0.044
246R-1, 66–70 (Piece 19)	2052.82	283	Dark	25	4.1	0.702691	±0.000015	59	0.045
247R-1, 30–33 (Piece 8)	2057.01	285	Dark	35	4.4	0.702787	±0.000014	52	0.048
247R-1, 46–50 (Piece 12)	2057.16	285	Halo	60	NA	0.702781	±0.000014	52	0.071
249R-1, 71–76 (Piece 24)	2071.91	291	Dark	30	4.2	0.702659	±0.000015	57	0.030
250R-1, 98–102 (Piece 28)	2081.40	291	Halo	25	3.6	0.702697	±0.000015	59	0.051
251R-1, 12–17 (Piece 4)	2090.08	293	Patch	60	NA	0.703039	±0.000014	60	0.080
251R-1, 72–76 (Piece 11)	2090.62	293	Dark	35	4.0	0.702739	±0.000013	50	0.030
251R-1, 76–80 (Piece 12)	2090.80	293	Patch	60	NA	0.702805	±0.000014	52	0.065
251R-1, 105–109 (Piece 20)	2091.36	293	Dark	20	4.1	0.702721	±0.000015	53	0.046
252R-1, 4–8 (Piece 2)	2099.44	293	Patch	60	NA	0.702803	±0.000014	51	0.035
252R-1, 15–20 (Piece 5)	2099.55	293	Patch	80	3.3	0.702971	±0.000014	60	0.051

Note: NA = not analyzed.

tion mass spectrometry (TIMS) in the Radiogenic Isotope Geochemistry Laboratory at the University of Michigan. Approximately 30 mg of powdered sample underwent a standard HF-HNO_3 dissolution before splitting and spiking for separate isotope and concentration determinations. Split samples were evaporated to incipient dryness then taken up in 0.2 mL of 3M HNO_3 before loading on fresh, cleaned Sr-Spec columns with a resin bed volume of ≈0.07 mL. Major elements were eluted with 1 mL of 3M HNO_3 before collecting Sr in 1 mL of H_2O. Spiked samples were treated in a similar fashion, although eluted with a lesser volume of 3M HNO_3 (≈0.6 mL), to retain some Rb in the Sr cut for TIMS-ID analysis. The acid wash was saved for each sample and Rb separated by conventional cation exchange resin techniques when necessary.

Strontium isotopic compositions ($^{87}Sr/^{86}Sr$ ratios) were determined by loading samples on single Re filaments with a $TaCl_5$ solution and 5% phosphoric acid. Samples were analyzed on a V.G. Sector multiple collector mass spectrometer, "Big Norm," using a $2.0 \pm 0.2 \times 10^{-11}$ A ion beam with at least 200 ratios collected in a multidynamic mode and normalized to $^{86}Sr/^{88}Sr = 0.1194$. NIST SRM 987 yielded $^{86}Sr/^{88}Sr = 0.710246 \pm 18$ (2σ, $N = 70$) over the period of analysis (July 1993–July 1994).

Rubidium and strontium concentrations were determined by TIMS-ID using single Re filaments and a similar loading technique, with Rb analyzed at a low current (≈1 A) preceding the Sr determination. Rb duplicate analyses conducted using conventional cation exchange resin and run on Ta-Re triple filaments were in close agreement with the single filament analyses. Full analytical procedural blanks were < 50 pg for both Rb and Sr.

RESULTS AND DISCUSSION

Alteration Petrography and Mineralogy of Rocks Recovered from Hole 504B on Leg 148

Alteration effects in the rocks recovered during Leg 148 are generally similar to those in the immediately overlying dikes (Alt et al., 1995; Laverne et al., 1995), and the main alteration features in hand specimen are illustrated in Figure 6. The petrography described in detail in Alt, Kinoshita, Stokking, et al. (1993) and Vanko et al. (this volume) is briefly summarized here, along with the results of this study. The rocks are fine- to medium-grained diabase dikes, comprising olivine, clinopyroxene, plagioclase, and accessory titanomagnetite, trace sulfides, and minor spinel. The rocks contain variable amounts (1%–8%) of plagioclase phenocrysts, glomerocrysts, and megacrysts. The phenocrysts are mainly bytownite (An_{70}–An_{80}) in composition, but the cores of plagioclase megacrysts range up to An_{90}. Plagioclase phenocrysts and megacrysts are commonly zoned, with the calcic cores having a sharp break in composition to a variably zoned mantle, about 0.1 mm wide, which is in turn rimmed by more sodic plagioclase (Dick, Erzinger, Stokking, et al., 1992; Alt, Kinoshita, Stokking, et al., 1993; Laverne et al., 1995; Vanko et al., this volume). Olivine phenocrysts generally make up 1%–2% of the rocks, and clinopyroxene phenocrysts are present in amounts less than 1%.

All samples exhibit at least some effects of hydrothermal alteration. The least altered rocks, which are dark gray in color, are affected by a pervasive "background" alteration and are 10%–40%

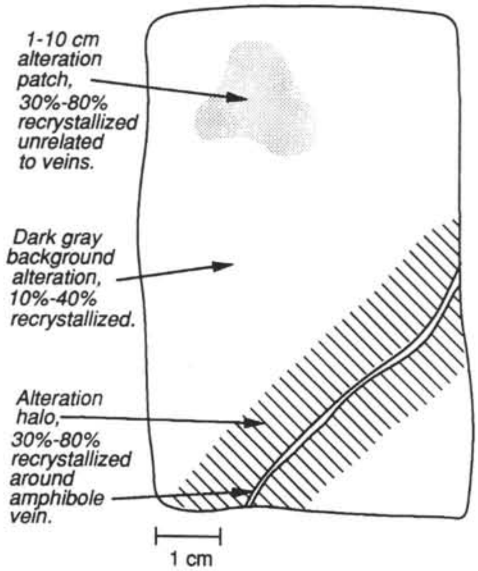

Figure 6. Sketch illustrating types of alteration in the lower dikes of Hole 540B. See text for further description.

recrystallized to secondary minerals. Olivine is generally totally replaced by chlorite, mixed-layer chlorite-smectite, quartz, talc + magnetite, and minor amphibole, plus sulfide minerals, although relict olivine is present in some of the least altered rocks. Talc and Fe-bearing talc are present replacing olivine and filling pores in the less altered rocks (Vanko et al., this volume). Plagioclase is slightly altered to albite-oligoclase, and pyroxene is partly altered to amphibole with magnetite blebs. Amphiboles range from actinolite to magnesiohornblende in subequal amounts. The igneous titanomagnetite contains ilmenite exsolution lamellae and is partly altered to titanite.

Veins are common, and consist of five types: amphibole ± chlorite ± accessory titanite veins are the most common, and chlorite ± accessory titanite veins are next in abundance; two epidote veins and one each of laumontite and quartz + chlorite + actinolite were also observed (Alt, Kinoshita, Stokking, et al., 1993). Multiple generations of mutually crosscutting amphibole veins occur, and veins of epidote and quartz cut across both amphibole and chlorite veins. Vein amphiboles range in composition from actinolite to magnesiohornblende (Fig. 3; Vanko et al., this volume).

Light-colored alteration halos are common around amphibole veins and are less well developed along chlorite veins (Fig. 6). The halos range from a few millimeters up to 2 cm wide, and are more intensively recrystallized than the adjacent dark gray host rock (30%–80% vs. 10%–40%, respectively). Olivine in the alteration halos is completely replaced by amphibole. The rims and mantles of igneous plagioclase are commonly partly replaced by secondary calcic plagioclase, which generally makes up a few percent (mostly <5%) of the rock. This secondary plagioclase mostly ranges from laboradorite to anorthite (An_{75}–An_{95}), and is consistently more calcic than the igneous plagioclase that it replaces (Laverne et al., 1995; Vanko et al., this volume). Patches and veins of albite-oligoclase ± chlorite also replace igneous plagioclase and cut the secondary calcic plagioclase, leading to the presence of subequal amounts of sodic and calcic secondary plagioclase. Pyroxene is extensively to completely replaced by amphibole, and titanomagnetite is strongly to totally altered to titanite. Amphiboles range from actinolite to magnesiohornblende, with the latter about twice as abundant as the former.

The rocks commonly exhibit 1- to 10-cm-sized, lighter colored alteration patches, in which the rock is intensively recrystallized (40%–80%; Fig. 6). The mineralogy of these patches is similar to the alteration halos around veins, but the alteration patches are unrelated to veins (Fig. 6). Some of these patches (e.g., Sample 148-504B-252R-1, 15–20 cm) clearly formed around primary pore space, where 1- to 5-mm-sized former vugs are now filled with needle-like amphibole. Similar features are observed throughout the dike section, and the patches probably represent more extensive hydrothermal reaction around locally enhanced primary pore spaces (Alt et al., 1985, 1989b, 1995; Zuleger et al., 1995; Bach et al., this volume).

Amphibole is the most common secondary mineral present both in veins and replacing pyroxene within the rocks, and is particularly abundant in the alteration halos and patches. Figure 3 shows the dramatic increase of the modal abundance of amphibole with depth in the lower dikes. Amphibole compositions range from actinolite to magnesiohornblende, even within a single thin section or vein, which is similar to the immediately overlying dikes (Alt et al., 1995; Laverne et al., 1995; Vanko et al., this volume). Ti contents of Leg 148 amphiboles continue the high values observed in the overlying lower dikes (1600–2000 mbsf, Fig. 3; Alt et al., 1995).

Oxygen Isotopes

Whole-rock samples from Leg 148 have $\delta^{18}O$ values of 3.3‰ to 4.5‰ (Table 1) and are depleted in ^{18}O relative to fresh MORB ($\delta^{18}O$ = 5.8‰ ± 0.2‰; Taylor, 1968; Muehlenbachs and Clayton, 1972). The Leg 148 values are generally lower than those in the overlying dikes, continuing the trend of decreasing $\delta^{18}O$ values with depth in the sheeted dikes (Fig. 5; Alt et al., 1986a, 1989b, 1995). There is a correlation of decreasing $\delta^{18}O$ with increasing percent recrystallization of the Leg 148 rocks (Fig. 7A). The less altered dark gray rocks have $\delta^{18}O$ = 4.0‰–4.4‰, whereas all but one of the more intensively altered halos and patches have $\delta^{18}O$ less than 3.7‰. This general trend is similar to that for the immediately overlying lower sheeted dikes (1550–2000 mbsf; Alt et al., 1995). The slightly lower $\delta^{18}O$ values of the Leg 148 whole-rock samples results in part from the greater intensity of recrystallization of these rocks to low-$\delta^{18}O$ secondary phases than shallower samples (Fig. 7A), but higher temperatures of alteration may also have contributed to the lower $\delta^{18}O$ values of the Leg 148 rocks. The latter is suggested by the lower $\delta^{18}O$ of least altered (dark gray) rocks from Leg 148 compared to the immediately overlying dikes, with little or no significant increase in the proportion of secondary minerals present (Fig. 7A).

The one Leg 148 sample that plots off this trend (Sample 148-504B-246R-1, 26–30 cm) is classified as an alteration patch (40% recrystallized), but actually consists of a small centimeter-sized amphibole-rich patch surrounded by less altered dark gray host rock. The latter portion of the sample is only slightly altered and contains relict olivine, and it may be that the thin section is not representative and that the sample is actually predominantly the dark gray host rock (this inference is supported by Sr isotopic analysis and sulfur contents, described in the following sections). Trends of increased $\delta^{18}O$ in more intensively altered zones occur in the upper dikes (Fig. 7B), and are due to the formation of later, lower temperature phases (e.g., zeolites) in these zones, plus progressive ^{18}O-enrichment of hydrothermal fluids through water-rock interactions (Alt et al., 1986b, 1995). No lower temperature phases were observed in Sample 148-504B-246R-1, 26–30 cm, however.

Sulfide Mineralogy and Sulfur Contents

The cursory descriptions of sulfide minerals made aboard the *Joides Resolution* (Alt, Kinoshita, Stokking, et al., 1993) are supplemented by the observations presented here. Pyrrhotite, pyrite, chalcopyrite, and magnetite occur as 2- to 30-µm inclusions in plagioclase, and are relict igneous sulfide minerals. Similar, but slightly larger (up to 100 µm), grains occur in interstitial areas. The globular shapes of some of these grains suggest that they are recrystallized igneous phases, but others may be of secondary origin.

Secondary pyrite and chalcopyrite occur as 2- to 200-µm grains in talc + magnetite pseudomorphs after olivine phenocrysts. Small (1–10 µm) grains of secondary chalcopyrite and pyrrhotite occur with

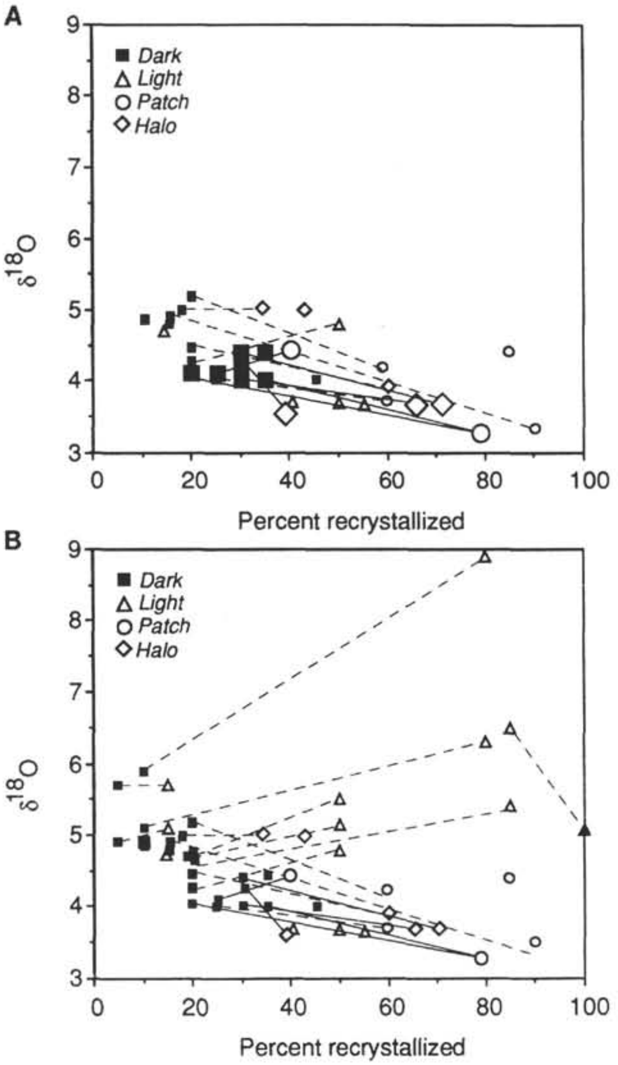

Figure 7. Whole-rock $\delta^{18}O$ vs. percent alteration (modal percent of secondary alteration minerals) for background dark gray diabase and alteration halos and patches. **A.** Data for lower sheeted dikes (below 1550 mbsf), Leg 148 samples shown as large symbols with dashed lines. Note general trend of lower $\delta^{18}O$ with increasing recrystallization for the lower dikes, which results from increasing recrystallization and higher temperatures of alteration in the more intensively altered patches and halos. **B.** Data for entire sheeted dikes and transition zone. Note trend toward increased $\delta^{18}O$ with increasing recrystallization for upper dikes and transition zone. This results from superimposed lower temperature alteration effects in the intensively altered light colored rocks, patches, and halos. Open triangles indicate generally light colored rocks, which are mixtures of halos or patches and dark gray rocks. Solid triangle is altered glassy pillow rim (after Alt et al., 1995). See text for discussion.

similarly sized grains of secondary magnetite in amphibole replacing clinopyroxene. Irregularly shaped, porous grains and aggregates of secondary pyrite and/or chalcopyrite, up to 100 µm in size, replace silicates in many samples.

In general, sulfide minerals are more common in the dark gray rocks affected by pervasive background alteration than in the highly altered patches and halos, where sulfide minerals are rare. There is a general decrease in sulfur contents with increasing percent alteration (Fig. 8), corresponding to the breakdown of igneous sulfides and loss of sulfur from the rocks. The Leg 148 samples continue the trend of S depletion observed in the lower dikes on Leg 140 (1550–2000 mbsf in Fig. 4; Alt et al., 1995). The S-depleted rocks also correspond to decreased Cu contents, consistent with loss of metal sulfide minerals (Fig. 4). The rocks exhibit variable depletions of Zn as the result of control by other phases in the rocks (Bach et al., this volume). Sulfur extractions from four samples for sulfur isotopic analyses are consistent with the X-ray fluorescence (XRF) analyses, with the halos having much lower S contents than the other rocks (Table 2). The S content of the alteration patch (Sample 148-504B-246R-1, 26–30 cm, see above) is relatively high ($S_{(tot)}$ = 435 ppm): this sample actually consists of a 1-cm patch plus the surrounding less altered host rock, and exhibits anomalous O and Sr isotopic compositions relative to other alteration patches. The bulk sample is probably less recrystallized than the other highly altered samples that show greater ^{18}O depletions and S losses. Sulfur in the low-S alteration halos is predominantly sulfate, whereas sulfur in the higher S, less altered rocks is mainly sulfide (Table 2), consistent with previous results from the lower dikes (Alt et al., 1995).

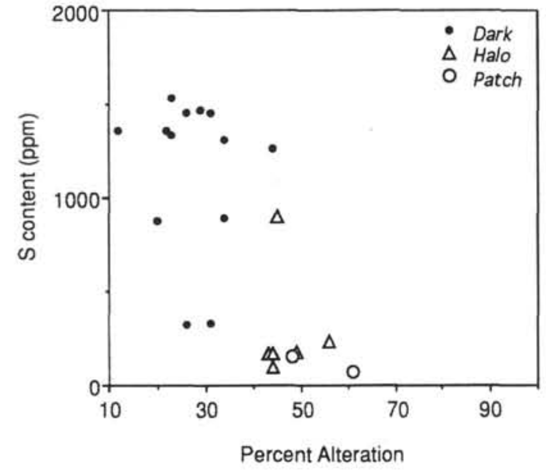

Figure 8. Sulfur content vs. recrystallization (proportion of secondary minerals) for background dark gray diabase and alteration halos and patches. Sulfur contents from shipboard data (Alt, Kinoshita, Stokking, et al., 1993) and Table 2. There is a general trend of decreasing S contents with increasing hydrothermal recrystallization.

Table 2. Sulfur data for Leg 148 samples from Hole 504B.

Core, section, interval (cm)	Depth (mbsf)	Unit	Type	Sulfide (ppm)	Sulfate (ppm)	Total S (ppm)	SO_4/ Total S
148-504B-							
241R-1, 95–98 (Piece 19)	2017.45	276	Halo	10	60	70	0.86
246R-1, 26–30 (Piece 9)	2052.50	283	Patch	280	155	435	0.36
246R-1, 66–70 (Piece 19)	2052.82	283	Dark	340	178	518	0.34
250R-1, 98–102 (Piece 28)	2081.40	291	Halo	10	153	163	0.94

Sr Isotopic Compositions and Sr Concentrations

Sr is a useful tracer for seawater-crustal interactions because the $^{87}Sr/^{86}Sr$ ratios of seawater (0.7091) and fresh basalt (≈0.7025) are significantly different and there are no temperature- or mineral-dependent isotopic fractionations of Sr. Thus, Sr isotope ratios of altered rocks, minerals, and fluids can provide a measure of the degree of interaction of seawater with the crust. Results of strontium isotopic analyses and Rb and Sr contents of samples from the lower sheeted dikes (1550–2111 mbsf, from Legs 137, 140, and 148) are presented in Table 1 and shown in Figures 5, 9, and 10. As the rubidium contents are extremely low (30–400 ppb) and these rocks are only 5.9 m.y. old, the age correction to the $^{87}Sr/^{86}Sr$ ratio for Rb decay is insignificant. The measured ratios are plotted on the relevant diagrams and used in the following discussion.

The lower dikes have a restricted range of whole-rock $^{87}Sr/^{86}Sr$ ratios of 0.70265–0.70304 (Table 1). These are only slightly elevated

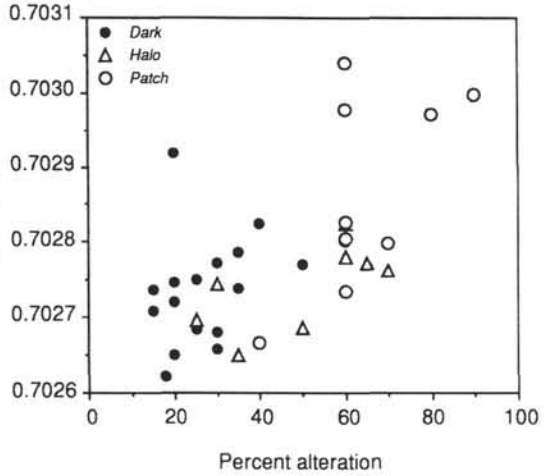

Figure 9. Plot of $^{87}Sr/^{86}Sr$ ratios vs. percent alteration (the proportion of secondary minerals) for more intensively altered patches and halos, plus background dark gray samples from the lower sheeted dikes (Legs 148, 137, and 140).

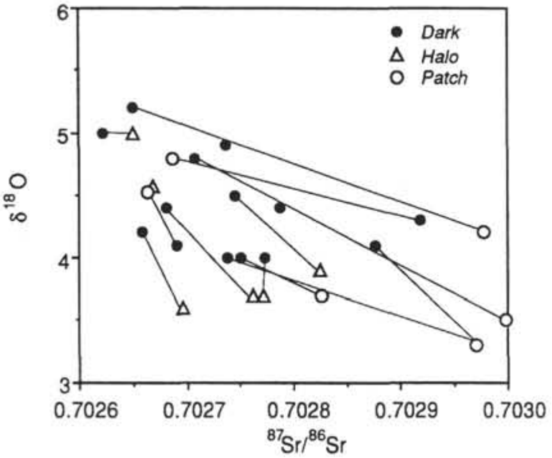

Figure 10. $\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$ for dark gray background and more highly altered patches and halos from the lower dikes of Hole 504B (>1550 mbsf; data from Table 1).

toward seawater composition relative to the lowest value of 0.7025 reported from Hole 504B, which is presumably near the primary MORB value for Site 504 (Shimizu et al., 1989). There is a general trend toward higher $^{87}Sr/^{86}Sr$ ratios with increasing alteration (Fig. 9), confirming that the elevated ratios are the result of alteration of the rocks by seawater-derived hydrothermal fluids. Sr contents of the rocks generally range from 48 to 62 ppm, although one vein halo is strongly enriched in Sr (89 ppm) (Table 1). The Sr contents of the rocks do not correlate either with Sr isotope ratios or with alteration type or extent. This implies that strontium was exchanged between the host rocks and hydrothermal fluids but that there was little change in concentration of Sr in the rocks and consequently, the fluids, in the lower sheeted dikes.

The correlation between $^{87}Sr/^{86}Sr$ and the abundance of secondary minerals in Figure 9 indicates that the rocks are mixtures of secondary minerals, which record the isotopic composition of the hydrothermal fluid, with igneous phases, which retain their original MORB isotopic composition. The general trend of increasing $^{87}Sr/^{86}Sr$ with decreasing $\delta^{18}O$ (Fig. 10) similarly reflects these varying extents of recrystallization, but lower $\delta^{18}O$ values may also result in part from higher temperatures of alteration for the more intensively altered patches and halos.

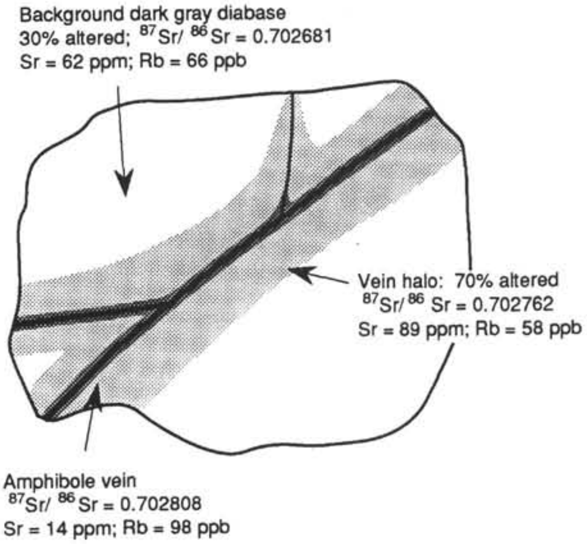

Figure 11. Sketch of Sample 148-504B-239R-1, 45–51 cm, from which the dark gray background diabase, vein halo, and amphibole vein were separated and analyzed for $^{87}Sr/^{86}Sr$ and Rb-Sr contents, as indicated on the sketch. See text for discussion.

Figure 11 shows a sketch of Sample 148-504B-239R-1, 45–51 cm (2000.85 mbsf), from which the amphibole vein, its associated alteration halo, and the adjacent dark gray host rock were analyzed for $^{87}Sr/^{86}Sr$. There is a slight increase in $^{87}Sr/^{86}Sr$ from the host rock (0.70268), to the alteration halo (0.70276), to the amphibole vein itself (actinolitic hornblende = 0.70281). This illustrates the effect of varying amounts of recrystallization on Sr (and O) isotopic compositions of the rocks, but also points out that in this case the circulating fluid, as represented by the vein amphibole isotopic composition, had a higher $^{87}Sr/^{86}Sr$ ratio than those measured for the host rock. A second amphibole (actinolite) vein at 1672 mbsf has a somewhat higher ratio (0.70316), and a chlorite vein at 1833 mbsf has $^{87}Sr/^{86}Sr$ = 0.70345, with both of these veins having higher values than the nearby whole rocks (Fig. 5; Table 1). Two epidote veins from the lower dikes have Sr isotope ratios of 0.7034 and 0.7038, which are higher than any whole-rock sample from the lower dikes (Fig. 5; Table 1). These data indicate two important points: (1) the Sr isotopic compositions of hydrothermal fluids in the lower dikes were variable; and (2) the $^{87}Sr/^{86}Sr$ ratios of hydrothermal fluids circulating in fractures were higher than those measured for whole rocks, which is a consequence of the partial recrystallization of the rocks.

The main differences in mineralogy between the patches and halos vs. the host rocks are the much greater abundance of secondary minerals, particularly amphibole, and the presence of secondary calcic plagioclase in the patches and halos (Fig. 12). Although amphibole is by far the most abundant secondary mineral in the rocks (Figs. 12, 13), amphibole has very low Sr contents (14 ppm measured for Sample 148-504B-239R-1, 45–51 cm; Table 1), so Sr contents and isotopic compositions of the rocks are probably dominantly controlled by the formation of secondary calcic and sodic plagioclase, both of which can contain significantly more Sr (Blundy and Wood, 1991; Berndt et al., 1988). Moreover, igneous clinopyroxene contains less Sr than magmatic plagioclase to begin with (e.g., Kuehner et al., 1989; Dunn and Sen, 1994), so replacement of pyroxene by amphibole would have much smaller influence on the Sr contents and isotopic compositions of the rocks than reactions involving plagioclase. Whole-rock Sr contents of the lower dikes exhibit a slight positive correlation with Na_2O (Fig 14), consistent with the presence of variable amounts of plagioclase in the rocks influencing whole-rock Sr contents. No data for the Sr contents or Sr isotopic compositions of igneous or the various secondary plagioclases (calcic or sodic)

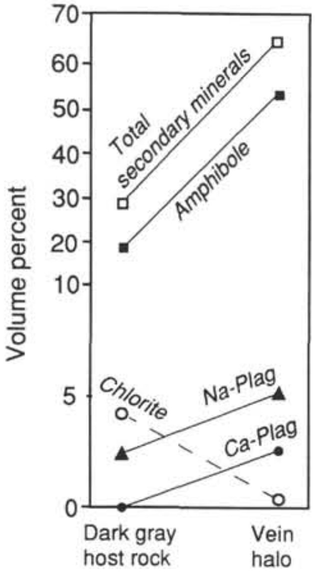

Figure 12. Modal data for secondary minerals in different alteration zones of Sample 148-504B-239R-1, 45–51 cm (see Fig. 11). Amphibole, sodic plagioclase, and calcic plagioclase increase in the alteration halo, whereas chlorite decreases relative to the adjacent dark gray host rock. Accessory ilmenite and trace sulfide minerals are less abundant in the vein halo than in the dark gray host rock. See text for discussion. Data obtained by point counting 500 points in each zone of the thin section.

from Hole 504B are available to further test the mineralogical control of whole-rock compositions inferred here.

Although anhydrite mineral separates were not analyzed for this study, one anhydrite rich whole-rock sample containing 4860 ppm sulfate S was analyzed (Sample 140-504B-214R-1, 73–76 cm; Table 1; Alt et al., 1995). The Sr content of this sample is not significantly different from other samples of alteration patches from the lower dikes, but it has one of the highest $^{87}Sr/^{86}Sr$ ratios (Table 1).

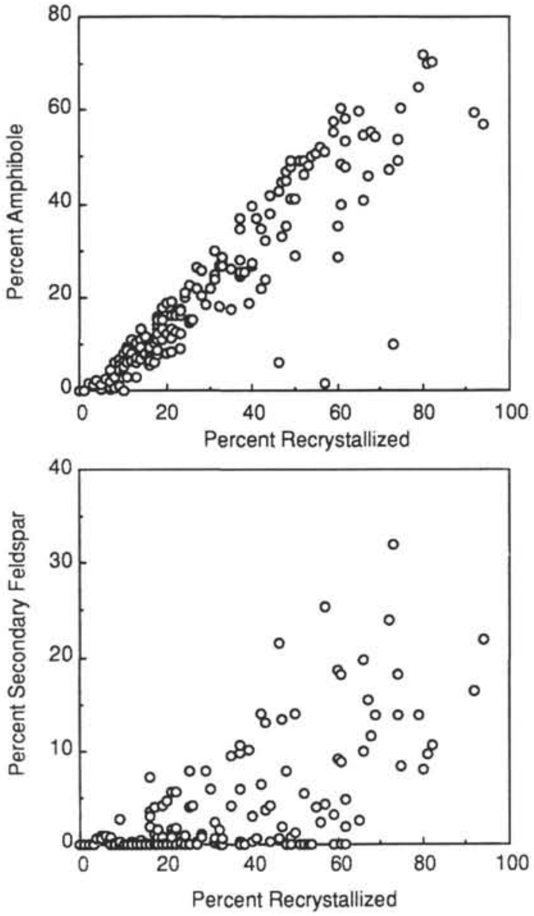

Figure 13. Modal data for amphibole and secondary plagioclase (sodic plus calcic) in the lower sheeted dikes of Hole 504B. Although amphibole is by far the most abundant secondary phase, significant amounts of secondary feldspar are present. Data from Dick, Erzinger, Stokking, et al. (1992) and Alt, Kinoshita, Stokking, et al. (1993).

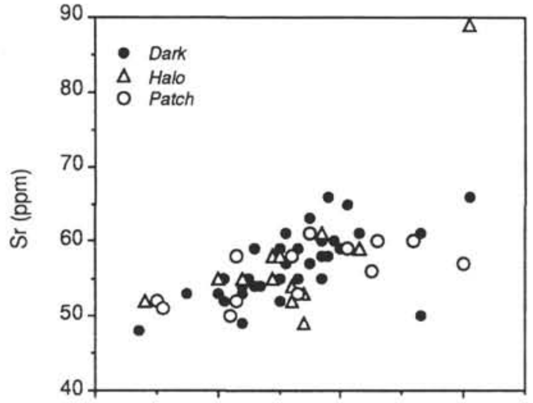

Figure 14. Whole-rock Sr and Na_2O contents for the lower dikes from Hole 504B. See text for discussion.

Relationship of Lower Dikes from Hole 504B to Hydrothermal Vent Fluids

The high-temperature (~350°C) end-member hydrothermal vent fluids exiting mid-ocean ridges have $^{87}Sr/^{86}Sr$ ratios of 0.70279–0.70465 (Palmer and Edmond, 1989). Hydrothermal fluids from three sites on the East Pacific Rise (EPR) have $^{87}Sr/^{86}Sr = 0.70285$–0.70465 with an average value of 0.7038 ± 0.0005 (1σ), whereas vent fluids sampled from two sites on the Mid-Atlantic Ridge have low $^{87}Sr/^{86}Sr$ ratios of 0.7028–0.7029 (Campbell et al., 1988). Sr isotopic compositions of vents can vary within a single vent field: e.g., at 21°N on the EPR vent fluids have $^{87}Sr/^{86}Sr$ values of 0.70285 to 0.70344. The Sr contents and isotopic compositions of hydrothermal fluids are functions of reactions occurring at different temperatures along the recharge and reaction zone pathways (Berndt et al., 1988), and the range in $^{87}Sr/^{86}Sr$ ratios of different vent sites has been attributed to varying amounts of seawater reacting with the crust, different fluid pathways, mixing of fluids in the subsurface, and differing amounts of seawater and hydrothermal Sr precipitated as anhydrite and epidote, respectively (Palmer and Edmond, 1989).

Petrographic evidence indicates multiple stages of alteration at varying temperatures and solution compositions in the lower dikes of Hole 504B (Alt et al., 1995; Laverne et al., 1995; Vanko et al., this volume). Secondary calcic plagioclase and magnesiohornblende formed early in alteration patches and vein halos at high temperatures (>400°C). This was followed by the formation of secondary sodic plagioclase, actinolite, and chlorite throughout the rocks at lower temperatures (250°–350°C), and then by deposition of epidote and quartz in crosscutting veins at 310°–320°C. Finally, late laumontite and prehnite formed locally in small amounts at <250°C.

The high temperatures of initial reactions in alteration halos and patches and the slight reaction of plagioclase to secondary calcic plagioclase in these zones are consistent with predictions of reactions thought to occur in the subsurface reaction zones for hydrothermal vent fluids (Berndt et al., 1988, 1989; Vanko et al., this volume). Berndt et al. (1988, 1989) suggest that, compared to seawater, hydrothermal fluids entering such reaction zones have decreased Sr/Ca, Na/Ca, and Sr and Mg contents as the results of chloritization and albitization of plagioclase and precipitation of anhydrite in the overlying recharge zone. Analysis of secondary calcic plagioclase and magnesiohornblende would provide the best constraints on the Sr isotopic compositions of hydrothermal fluids during the early high temperature alteration in the reaction zone, but these have not yet been analyzed. The $^{87}Sr/^{86}Sr$ ratios of actinolitic hornblende (0.7028), actinolite (0.70316), and chlorite (0.70345) veins from the lower dikes in Hole 504B document variable fluid compositions in the lower dikes. These Sr isotopic compositions fall within the low end of the range for seafloor hydrothermal vent fluids (0.7028–0.7046).

Abundant epidote and epidote + quartz veins formed at temperatures of 250°–350°C associated with sulfide mineralization in the transition zone and in the uppermost dikes of Hole 504B from upwelling hydrothermal fluids, as these mixed with cooler seawater circulating in the overlying volcanic section (Alt et al., 1986a, 1986b). Epidote veins of the lower dikes and in the uppermost dikes and transition zone have the same chemical compositions, formed over a similar range of temperatures (300°–350°C), and occur in veins that cut earlier alteration phases, indicating that they are all part of the same alteration stage at Site 504 (Alt et al., 1986a, 1986b, 1989b, 1995). The Sr isotopic compositions of epidote from the lower dikes are similar to that of epidote from 650–800 m shallower in the transition zone ($^{87}Sr/^{86}Sr$ ratios of 0.7034–0.7038 and 0.7038, respectively; Fig. 5; Table 1; Kawahata et al., 1987). These similarities suggest that epidote records the $^{87}Sr/^{86}Sr$ of the end-member upwelling hydrothermal fluid at Site 504. These ratios for epidotes fall within the range for vent fluids from the EPR (0.7038 ± 0.0005 (1σ); Palmer and Edmond, 1989). As epidote occurs in veins that cut earlier amphibole and chlorite veins throughout the dikes, the epidotes document an increase in the $^{87}Sr/^{86}Sr$ ratios of hydrothermal fluids compared to earlier stages.

Strontium Isotopic Profile Through the Upper Ocean Crust

A profile of previously published and new whole-rock $^{87}Sr/^{86}Sr$ ratios through the upper ocean crust at Site 504 is shown in Figure 5. There is a general trend in the volcanic section from moderately elevated ratios ($^{87}Sr/^{86}Sr \approx 0.7035$) at the top toward primary MORB compositions ($^{87}Sr/^{86}Sr \approx 0.7025$–$0.7027$) at the base of the extrusive section. This suggests a generally decreasing seawater effect with increasing depth in the lavas, consistent with other chemical, mineralogical, and isotopic evidence (Alt et al., 1986a, 1989a, 1989b). Alteration within the extrusive sequence is heterogeneous, however, with oxidation halos around veins and intensive alteration of glassy and hyaloclastic materials at pillow margins to smectite ± carbonate. The published Sr analyses are for least altered rocks affected by the slight smectitic background alteration, and do not generally include the more intensely altered material. Secondary smectite and carbonates from the volcanic sections of Hole 504B and nearby Hole 896A have highly elevated $^{87}Sr/^{86}Sr$ ratios (up to ~0.7088; Staudigel and Hart, 1985; Teagle et al., this volume), and a volcanic breccia from Hole 896A has $^{87}Sr/^{86}Sr = 0.7048$ (Teagle et al., this volume). Moreover, Formation MicroScanner images of the Hole 896A borehole by Brewer et al. (1994) suggest that breccias can comprise a significant proportion of the volcanic section (i.e., possibly up to half of the 300 m volcanic section at that site). Inclusion of such highly altered breccias in the database of Figure 5 would probably significantly affect the Sr isotopic composition of the uppermost crust.

Rocks from the transition zone (846–1055 mbsf) and associated stockwork mineralization all have elevated $^{87}Sr/^{86}Sr$ ratios (≈ 0.703–0.707) that indicate a significant component of seawater-derived strontium in these rocks. The data are generally clustered in the range $^{87}Sr/^{86}Sr \approx 0.7030$–$0.7045$, which is similar to the variation displayed by high-temperature black smoker vent fluids (Palmer and Edmond, 1989), but still exhibit a wide range about the end-member hydrothermal fluid composition inferred from epidotes from Hole 504B (0.7034–0.7038). Alteration of rocks from the transition zone occurred in a region of fluid mixing, so the high $^{87}Sr/^{86}Sr$ of some whole-rock samples are the result of reaction of the rocks with mixtures of low-$^{87}Sr/^{86}Sr$ hydrothermal fluids and seawater. Similar effects are seen in the subsurface stockwork from the Galapagos Spreading Center (Ridley et al., 1994). Whole-rock values less than 0.7038 in this zone would then reflect variable exchange of igneous Sr in the rock with hydrothermal Sr in upwelling fluids.

There is some scatter in $^{87}Sr/^{86}Sr$ (≈0.7025–0.7040) of the uppermost sheeted dikes (1050–1350 mbsf; Fig. 5). Sr isotope analyses of dikes recovered on ODP Leg 111 (1350–1562 mbsf) have only been made on relatively fresh material to address problems of igneous petrogenesis (Kusakabe et al., 1989; Shimizu et al., 1989), so $^{87}Sr/^{86}Sr$ ratios in this interval fall close to primary MORB values. The large scatter in Sr isotopic compositions of the uppermost dikes must decrease with depth to the variably altered rocks of the lower dikes (>1600 mbsf). The same effect is seen in sulfur isotopic compositions of the rocks: $\delta^{34}S$ decreases downward from values of 3‰–5‰ in the transition zone to about 0‰–1‰ in the upper dikes (Fig. 5), reflecting decreasing seawater influence downward from the mixing zone into the dikes (Alt et al., 1989b). Whole-rock $\delta^{18}O$ values also decrease downward into the dikes as the result of diminishing lower temperature effects (^{18}O enrichments at <200°–250°C), which are superimposed on higher temperature ^{18}O depletions in the rocks (Fig. 5; Alt et al., 1986b, 1995).

The lower dikes (1600–2100 mbsf) exhibit decreased Cu, Zn, and S contents (Fig. 4); progressively decreasing $\delta^{18}O$ (Fig. 5); the presence of small amounts of anhydrite locally replacing plagioclase and filling pore space in the rocks; increasing amounts of recrystallization (Fig. 4); the appearance of secondary magnesiohornblende, calcic plagioclase, and clinopyroxene (Fig. 2), and increasing Ti contents of amphiboles (Fig. 3). All of this was taken as evidence that the lower dikes were part of the so-called reaction zone, where metals and S are leached from the rocks at temperatures above 350°C and where hydrothermal vent fluids acquire their final compositions (Alt et al., 1995; Laverne et al., 1995; Zuleger et al., 1995; Vanko et al., this volume). The lower dikes have Sr isotopic ratios only slightly elevated above primary MORB values (Fig. 5), as discussed in the preceding sections.

Diabases from the Mid-Atlantic Ridge exhibiting alteration mineralogy and bulk chemistry (e.g., Cu and Zn losses) similar to those in the lower dikes of Hole 504B have been interpreted to be from the lower sheeted dikes, and to possibly represent a reaction zone for hydrothermal fluids (Gillis and Thompson, 1993). These rocks have $^{87}Sr/^{86}Sr$ ratios of 0.70260–0.70439, approaching the values for fresh basalts (0.70229 ± 0.00002) and overlapping that of nearby hydrothermal vent fluids (0.7028; Gillis and Thompson, 1993).

The low $^{87}Sr/^{86}Sr$ ratios of sheeted dikes from Hole 504B and the Mid-Atlantic Ridge differ from the uniformly high ratios for dikes from the Troodos and other ophiolites (0.7054 ± 0.0007 2σ for Troodos; Bickle and Teagle, 1992). This difference indicates a much greater seawater influence on the compositions of ophiolitic dikes than for dikes from oceanic crust in Hole 504B. The strontium data is consistent with the observed total recrystallization of dikes in Troodos and other ophiolites compared to the partial recrystallization of oceanic dikes from Hole 504B and elsewhere on the seafloor (Gillis and Thompson, 1993; Alt et al., 1995), as well as with data for other tracers (e.g., sulfur; Alt, 1994), which require much greater interaction of Troodos dikes with seawater than occurs in oceanic crust. These differences in alteration effects of ophiolites and ocean crust must be in some way related to the differences in tectonic setting, chemistry, and mineralogy of these crustal sections. The rocks of the ophiolites contain much greater amounts of volatiles, are more vesicular and perhaps more brecciated than oceanic crust, and tend to be more glassy, which would facilitate greater reaction with hydrothermal fluids. Moreover, there may be differences between reaction rates of seawater with oceanic basalts vs. the more felsic and mafic (e.g., boninitic) rocks of ophiolites.

Another difference in the data for Hole 504B and for the Troodos ophiolite is the good evidence for hydrothermal fluids having higher ^{87}Sr/^{86}Sr ratios than the rocks at Site 504. In contrast, the more uniformly elevated ratios throughout the various alteration types in the Troodos dikes, including epidosites, quartz-chlorite rocks, and background diabase, were interpreted to indicate that fluids and rocks had the same Sr isotopic compositions (Bickle and Teagle, 1992). This is a consequence of the much greater amounts of reaction of the Troodos dikes with seawater than in the oceanic rocks from Hole 504B. The low ^{87}Sr/^{86}Sr ratios of dikes and vein minerals from Hole 504B are consistent with the more MORB-like Sr isotopic compositions of vent fluids at modern mid-ocean ridges, compared to the high ratios inferred for hydrothermal fluids at Troodos (Bickle and Teagle, 1992).

SUMMARY AND CONCLUSIONS

Leg 148 deepened Hole 504B by 111 m, to a total depth of 2111 mbsf, and recovered diabase dikes similar to the immediately overlying rocks. Samples from the Leg 148 section exhibit a pervasive background alteration, in which the rocks are dark gray and are 10%–40% recrystallized. More intensively altered (30%–80% recrystallized) light colored zones are common and include halos along veins and centimeter-sized alteration patches unrelated to veins. Amphibole compositions range from actinolite to magnesiohornblende, even within a single thin section.

Trends observed in the overlying lower dikes (1600–2000 mbsf) continue in the Leg 148 section (2000–2111 mbsf). These include the local presence of magnesiohornblende and secondary calcic plagioclase, and high Ti contents of amphiboles. Cu and S contents of the more altered rocks are low as the result of breakdown and loss of igneous sulfides. Zn contents are also low in the Leg 148 rocks, as in the overlying lower dikes. Whole-rock δ^{18}O values of 3.3‰–4.5‰ for Leg 148 samples are low relative to unaltered MORB, and continue the trend of decreasing δ^{18}O with depth in the dikes. All of these trends reflect alteration at higher temperatures (>350°C) and greater extents of recrystallization than in the upper dikes. A sequence of alteration, from early higher temperature (up to 400°–500°C) reactions mainly in alteration halos and patches to lower temperature greenschist reactions throughout the rocks, to the formation of epidote and quartz in veins (at 300°–350°C), occurred in the Leg 148 section (2000–2111 mbsf), as in the overlying lower dikes (1600–2000 mbsf). Lower temperature effects, such as the formation of zeolites and prehnite, are scarce in the Leg 148 section and lower dikes compared to the upper dikes. All of the data for the new Leg 148 section of Hole 504B are consistent with the rocks being a continuation of the reaction zone where metals and sulfur are leached from the crust by hydrothermal fluids and transported to form metal sulfide mineralizations on or within the crust, or vent into seawater.

Sr contents of altered lower dikes (1560–2111 mbsf) are generally 48–62 ppm, and whole-rock ^{87}Sr/^{86}Sr ratios range from 0.70265 to 0.70304, only slightly elevated relative to fresh MORB values. The rocks were altered by seawater-derived hydrothermal fluids, with little change in the Sr concentrations of the rocks. Although amphibole is the most abundant secondary phase, the Sr isotopic compositions of the rocks are probably controlled by the abundance of secondary sodic and calcic plagioclase. Data for secondary vein minerals indicate that hydrothermal fluids had higher ^{87}Sr/^{86}Sr ratios than the rock and that the Sr isotopic compositions of hydrothermal fluids increased through time, from ~0.7028–0.70345 for formation of actinolitic hornblende, actinolite, and chlorite veins to 0.7034–0.7038 for epidote in crosscutting veins at 300°–350°C. The Sr isotopic compositions of all these minerals fall within the range for hydrothermal vent fluids, but the epidotes record the compositions of upwelling end-member black smoker-type hydrothermal fluids at Site 504. The low ^{87}Sr/^{86}Sr ratios and partial recrystallization of the sheeted dikes in Hole 504B differ from the uniformly high ^{87}Sr/^{86}Sr ratios and total recrystallization of sheeted dikes from the Troodos ophiolite. The oceanic dikes interacted with much smaller volumes of seawater than the ophiolitic rocks, which must be related in some way to the differences in tectonic setting, chemistry, and primary mineralogy of ophiolites and in situ ocean crust.

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