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 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 5.5-km-olde 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 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 δ18O values of 3.3–4.5% continue the trend of decreasing δ18O with depth. These trends reflect alteration at higher temperatures (>350°C) and greater extents of recrystallization 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.

Strontium isotopes of the lower sheeted dikes (1550–2111 mbsf) are generally 48–62 ppm, and whole-rock 87Sr/86Sr 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 87Sr/86Sr 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 87Sr/86Sr 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 87Sr/86Sr 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 rocks of the ocean crust.

SITE 504

The basement rocks sampled in Hole 504B comprise aphyric to highly phryic tholeiitic basalt, having moderately evolved mid-
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; 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.
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; Leverne 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_0.5-An_0.5) and minor secondary clinopyroxene appear in the lower dikes (Fig. 2). The abundance of zeolites decreases 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).

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).

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 x 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 C1F3 and converted to CO2 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 δ18O (‰) = 100 x [(18O/16O)sample - (18O/16O)SMOW]/(18O/16O)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 $\text{Fe}^{3+}/\text{Fe}^{\text{tot}}$ ratio is fairly constant with depth in the lower dikes ($\approx 0.25$), 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; Kasakabe 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).
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$_3$ 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 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; Lavener 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$_{100}$–An$_{90}$) 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 a pervasive "background" alteration and are ed by a pervasive "background" alteration and are 10%–40%
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 relic 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. The rims and mantles of igneous phases, but others may be of secondary origin. Globular shapes of some of these grains suggest that they are recrystallized igneous phases, but others may be of secondary origin. The modal increase 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 dike. Amphibole compositions range from actinolite to magnesiohornblende, even within a single thin section or vein, which is similar to the immediately overlying dike. Amphibole compositions range from actinolite to magnesiohornblende, even within a single thin section or vein, which is similar to the immediately overlying dike.

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

Oxygen Isotopes

Whole-rock samples from Leg 148 have $\delta^{18}O$ values of 3.3%e to 4.5%e (Table 1) and are depleted in $^{18}O$ relative to fresh MORB ($\delta^{18}O$ = 5.8%e ± 0.2%e; Taylor, 1968; Muehlenbachs and Clayton, 1972). The Leg 148 values are generally lower than those in the overlying dike sets, continuing the trend of increasing $\delta^{18}O$ values with depth in the sheeted dike (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 gray rocks have $\delta^{18}O$ = 4.0%e-4.4%e, whereas all but one of the more intensively altered halos and patches have $\delta^{18}O$ less than 3.7%e. This general trend is similar to that for the immediately overlying lower sheeted dike (1500-2000 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 dike sets, with little or no significant increase in the proportion of secondary minerals present (Fig. 7A).

The Leg 148 sample that plots off this trend (Sample 148-504B-249-R-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 relic 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 content, described in the following sections). Trends of increased $\delta^{18}O$ in more intensively altered zones occur in the upper dike (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-249-R-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 magnesite 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 + magnesite pseudomorphs after olivine phenocrysts. Small (1-10 µm) grains of secondary chalcopyrite and pyrrhotite occur with
decreased Cu contents, consistent with loss of metal sulfide minerals in Fig. 4; Alt et al., 1995). The S-depleted rocks also correspond to S depletion observed in the lower dikes on Leg 140 (1550-2000 mbsf of sulfur from the rocks. The Leg 148 samples continue the trend of general decrease in sulfur contents with increasing percent alteration altered patches and halos, where sulfide minerals are rare. There is a general trend of decreasing S contents with increasing hydrothermal recrystallization.

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.

<table>
<thead>
<tr>
<th>Core, section, interval (cm)</th>
<th>Depth (mbsf)</th>
<th>Unit Type</th>
<th>Sulfide (ppm)</th>
<th>Sulfate (ppm)</th>
<th>Total S (ppm)</th>
<th>SO\textsubscript{4} (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>148-504B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>241R-1, 95-98 (Piece 19)</td>
<td>2014.75</td>
<td>Halo</td>
<td>10</td>
<td>60</td>
<td>70</td>
<td>0.86</td>
</tr>
<tr>
<td>246R-1, 26-30 (Piece 9)</td>
<td>2052.90</td>
<td>Patch</td>
<td>280</td>
<td>155</td>
<td>435</td>
<td>0.36</td>
</tr>
<tr>
<td>246R-1, 66-70 (Piece 19)</td>
<td>2052.82</td>
<td>Dark</td>
<td>178</td>
<td>518</td>
<td>696</td>
<td>0.34</td>
</tr>
<tr>
<td>250R-1, 98-102 (Piece 28)</td>
<td>2081.40</td>
<td>Halo</td>
<td>153</td>
<td>163</td>
<td>316</td>
<td>0.94</td>
</tr>
</tbody>
</table>

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.

Sr Isotopic Compositions and Sr Concentrations

Sr is a useful tracer for seawater-crustal interactions because the \(^{87}\text{Sr}/^{86}\text{Sr}\) 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 \(^{87}\text{Sr}/^{86}\text{Sr}\) 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 \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of 0.70265-0.70304 (Table 1). These are only slightly elevated...
ground dark gray samples from the lower sheeted dikes (Legs 148, 137, and 140) for more intensively altered patches and halos, plus background dark gray samples from the lower sheeted dikes (Lego 148, 137, and 140).

Figure 9. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ 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. $\delta^{18}\text{O}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for dark gray background and more highly altered patches and halos from the lower dikes of Hole 504B (> 1550 mbsf; data from Table 1).

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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$. There is a slight increase in $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 1835 mbsf has $^{87}\text{Sr}/^{86}\text{Sr}$ = 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 these 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$_2$O (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)
Dark gray host rock

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).

**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 albition 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 87Sr/86Sr 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 (87Sr/86Sr 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 87Sr/86Sr of the end-member upwelling hydrothermal fluid at Site 504. These ratios for epidote 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 87Sr/86Sr 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 87Sr/86Sr 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 (87Sr/86Sr = 0.7035) at the top toward primary MORB compositions (87Sr/86Sr = 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, 1990b). Alteration within the extrusive sequence is heterogeneous, however, with oxidation halos around veins and intense 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 87Sr/86Sr ratios (up to ~0.7088; Staudigel and Hart, 1985; Teagle et al., this volume), and a volcanic breccia from Hole 896A has 87Sr/86Sr = 0.7048 (Teagle et al., this volume). Moreover, from MicroScan 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 87Sr/86Sr ratios (~0.7037-0.7070) that indicate a significant component of seawater-derived strontium in these rocks. The data are generally clustered in the range 87Sr/86Sr = 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 Sr/86Sr values of some whole-rock samples are the result of reaction of the rocks with mixtures of low-87Sr/86Sr 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 87Sr/86Sr (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 87Sr/86Sr 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: δ34S decreases downward from values of 5-8‰ 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 δ18O values also decrease downward into the dikes as the result of diminishing lower temperature effects (δ18O enrichments at <200°-250°C), which are superimposed on higher temperature δ18O 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 δ18O (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 clinoxyroxene (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; Lavene 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 87Sr/86Sr ratios of 0.7026-0.70439, approaching the values for fresh basalts (0.7029 ± 0.0002) and overlapping that of nearby hydrothermal vent fluids (0.7028; Gillis and Thompson, 1993). The low 87Sr/86Sr 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 hydrother-
nal 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 \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios than the rocks at Site 504. In contrast, the more uniformly elevated ratios throughout the various alteration types in the Troodos dikes, including epidodes, 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 \(^{87}\text{Sr}/^{86}\text{Sr}\) 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 lower 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^18O values of 3.3%–4.5%o for Leg 148 samples are low relative to unaltered MORB, and continue the trend of decreasing δ^18O 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 sulfate mineralizations on or within the crust, or vent into seawater.

Sr contents of altered lower dikes (1500–2111 mbsf) are generally 45–62 ppm, and whole-rock \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios range from 0.70265 to 0.70364, 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 \(^{87}\text{Sr}/^{86}\text{Sr}\) 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 \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios and partial recrystallization of the sheeted dikes in Hole 504B differ from the uniformly high \(^{87}\text{Sr}/^{86}\text{Sr}\) 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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