INTRODUCTION

Evidence for submarine hydrothermal activity along oceanic spreading centers has been accumulated from a large and diverse body of geochemical and geophysical data (e.g., Boström and Peterson, 1966; Wolery and Sleep, 1976; Humphris and G. Thompson, 1978), and the alteration of oceanic rocks by seawater has been the subject of intense study for the last few years. Previous studies of Deep Sea Drilling Project (DSDP) samples have found little evidence of high-temperature hydrothermal activity in the upper part of the oceanic crust. Instead, most of the alteration described appears to be the result of low-temperature interchange between basalt and seawater under ambient conditions on the seafloor. This type of alteration is most pronounced along fractures and open channelways and involves the growth of smectite, carbonate, and occasionally pyrite and phillipsite. Olivine crystals and interstitial glassy material within the basalts are frequently replaced by smectites and more rarely, carbonate, but the plagioclase feldspars and clinopyroxenes are normally unaffected. The resulting chemical changes usually involve notable increases in $\text{H}_2\text{O}$, $\text{Fe}_2\text{O}_3$, $\text{K}_2\text{O}$, $\text{Rb}$, $\text{Cs}$, and $\text{U}$ and smaller increases in total iron and $\text{Sr}$. $\text{TiO}_2$, $\text{Al}_2\text{O}_3$, $\text{P}_2\text{O}_5$, $\text{Nb}$, $\text{Zr}$, and $\text{Y}$ are usually considered to be little affected by alteration (e.g., Bass, 1976; Robinson et al., 1977). Several workers (e.g., Pritchard et al., 1979) have noticed an increase in the degree of alteration with age.

In contrast, DSDP Legs 64 and 65 found evidence for local hydrothermal activity at a high level in the ocean crust at several localities in the Guaymas Basin and at the mouth of the Gulf of California. Although most of the basalts recovered contained the assemblage smectite, carbonate, and pyrite and were considered to show typical low-temperature alteration, evidence for intense hydrothermal activity was reported from sediments adjacent to sill-intrusions in the Guaymas Basin (Einsel et al., 1980) and local alteration of basalt to chlorite and actinolite was observed at Site 482 at the mouth of the Gulf. Although these samples represented the first reported occurrence of hydrothermally altered basalts in DSDP drill holes in “normal” ocean crust, they were not thought to be representative of the alteration processes operating along this section of the East Pacific Rise. Subsequent work suggests that many of the other basalts sampled by Legs 64 and 65 were also affected by hydrothermal alteration. The main purpose of this chapter is to describe the alteration of these basalts in terms of their mineralogy and chemistry and to compare them with samples recovered from other DSDP sites.

### SAMPLING AND ANALYTICAL TECHNIQUES

To accomplish these objectives, 69 bulk-rock samples were collected for microprobe and fluorescence spectrometer analysis from Sites 482, 483, and 485 at the mouth of the Gulf during Leg 65. Wherever possible, multiple samples were taken from individual cooling units that showed variable degrees of alteration. No attempt was made to sample all of the chemical and lithological types recognized on ship, but the set is fairly representative of the compositional range encountered. These were supplemented by 13 samples of fresh glass in order to determine the initial compositions of the rocks. In addition, a set of 21 basalt samples and 7 glass samples were made available to us from Holes 474A, 477A, and 478, enabling us to investigate the nature of the alteration processes operating in the Guaymas Basin.

The electron microprobe analyses were made at Imperial College, using a Cambridge Instruments Microscan V probe fitted with a Link EDS detector. The probe was operated at an accelerating voltage of 15 kV, a specimen current of 0.01 µA, and a counting time of 100 s. The beam was focused to a minimum spot except when analyzing hydroxyl secondary minerals and carbonates, at which time a defocused beam was used. Microprobe analysis of secondary minerals poses special problems because of their high volatile content, small grain size, and inhomogeneity, either in the minerals or in the polishing. For most of the analyses reported here, the beam was defocused to 40 µm to reduce decomposition; nevertheless, some decomposition was always observed. The only instance in which loss of alkalalts was detected was in the zeolites from Holes 478 (Table 1) where a slight loss of Na with time was observed. A defocused beam could not be used for the sulfates in Hole 482C because the crystals were too small. Nevertheless, the analyses reported here showed a high degree of repeatability and, except for the reservations noted, are believed to be reasonably accurate.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>1</th>
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<th>3</th>
<th>4</th>
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<tbody>
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</tr>
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<td>0.05</td>
<td>--</td>
<td>--</td>
<td>0.02</td>
<td>--</td>
<td>0.04</td>
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<td>--</td>
<td>--</td>
<td>0.01</td>
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</tr>
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<td>8.74</td>
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<td>0.04</td>
<td>0.06</td>
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<td>0.08</td>
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<td>0.06</td>
<td>0.18</td>
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<td>84.38</td>
<td>82.44</td>
<td>85.20</td>
<td>84.90</td>
</tr>
</tbody>
</table>

Note: All analyses from Sample 478-45-3, 67–71 cm; 1–3, green smectites in groundmass; 4, zeolite replacing plagioclase (1) in Table 2; 5–7, zeolites replacing plagioclase (2) in Table 2; 8, groundmass zeolites. Values shown in wt. %.

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Major and trace element analyses were obtained using the Phillips X-ray fluorescence spectrometer at Imperial College. The Li and Sc data were obtained at Kings College, London, using an inductively coupled plasma spectrometer. Details of the analytical techniques have been published elsewhere and will not be reported in detail here. (Flower et al., 1979; Walsh, 1980). FeO determinations were carried out using the method of Whipple (1974).

Loss of ignition was determined for each sample by first drying the powder at 110°C for 24 hr. and then igniting it in a furnace at 1000°C until constant weights were obtained. The weight losses were corrected for the effects of oxidation of FeO during ignition.

SECONDARY MINERALS

The Guaymas Basin

The Guaymas Basin is an active spreading center formed during the last 3.5 m.y. and characterized by high sedimentation rates—in excess of 1200 m/m.y. Samples were obtained from a dolerite sill near the top of Hole 477A in the southern rift and from a massive dolerite sill at the base of Hole 478, which was drilled 12 km from Site 477 on the basin floor northwest of the south rift. Einsele et al. (1980) have presented convincing evidence that the intrusion of sills into the highly porous sediments of the Guaymas Basin was accompanied by thermal alteration of the sediments, marked changes in interstitial water chemistry, and large-scale expulsion of heated pore fluids. This process is thought to have created space for the intruding magmas and to have initiated hydrothermal systems which gave rise to the deposits of talc, pyrrhotite, and sulfides observed near fault scarps on the basin floor. Various changes have been recorded in the sediments adjacent to the sills sampled in this study, including the remobilization of silica, the formation of dolomite, and the recrystallization of clay minerals. Temperatures in the sediments are thought to have reached values of approximately 150°C.

Despite the locally intense thermal alteration suffered by the sediments, the basalts contain only minor amounts of secondary minerals. The Hole 477A samples contain small quantities of smectite and carbonate as fillings in radial fractures and as secondary minerals replacing olivine and groundmass material. Unfilled vesicles were observed just below the chilled margin. The samples from Hole 478 show similar amounts of smectite and, in addition, contain zeolites replacing both plagioclase and groundmass material. Microprobe analyses of these minerals are listed in Tables 1 and 2 and the compositional variations are shown in Figures 1 and 2.

Both the smectites and the zeolites in the Hole 478 samples show distinct differences in composition from the analyses reported for other DSDP sites. The zeolite species normally encountered in ocean floor basalts is the K-rich variety, philippsite. In the K₂O-Na₂O-CaO plot shown in Figure 1, they plot close to the base of the triangle, overlapping the plagioclase compositions from the same samples. When allowance is made for the possibility of Na loss during analysis as previously discussed, it seems likely that the spread of the zeolites towards the CaO apex is probably only an artifact. The smectites show a similar impoverishment in potassium relative to smectites from other DSDP sites with a similar FeO*/MgO ratio. With the exception of the smectites

![Figure 1. Distribution of plagioclases and zeolites from Hole 478 on a K₂O-Na₂O-CaO diagram. (Also shown are philippsites from Legs 37 and 49. Data sources: Scarfe and Smith, 1977; Robinson et al., 1977; Pritchard et al., 1979.)](image)

from Site 483, which will be discussed later, this seems to be a characteristic of the clay minerals recovered during Legs 64 and 65.

Site 474

Site 474 was located approximately 5 km from the continent/ocean-crust transition near the southeast tip of Baja California. The basalts sampled at this site represent the oldest material recovered from the ocean floor along the transect across the mouth of the Gulf of California. The sedimentation rates, although high, are significantly lower here than in the Guaymas Basin, and some extrusion of basalt occurred directly on the seafloor. Consequently, little of the intense sediment alteration noted in the Basin has been reported for this site. The average sedimentation rate at Site 474 was 160 m/m.y., but the rate increased during the Quaternary to 240 m/m.y. The drilling in Hole 474A penetrated a thick sedimentary sequence, followed by a few massive units and then interbedded pillows and massive basalts. A similar basement stratigraphy was encountered at the other sites drilled along the transect during Leg 65,
Figure 2. MgO and K$_2$O versus total iron as FeO$^*$ for smectites in basalts from Legs 64 and 65. (Also shown are typical smectite compositions from basalts affected by low-temperature alteration from both the Atlantic and Pacific oceans. Values shown in wt.%. Data sources: Pritchard et al., 1979; Humphris et al., 1980; Robinson et al., 1977.)
showing this structure to be typical of this section of the East Pacific Rise.

Other than the possible occurrence of minor chlorite in veins (reported by the shipboard party but not confirmed by subsequent study), the basalts recovered from Hole 474A appeared to show typical low-temperature secondary mineral assemblages. Fresh glass selvages showing little or no palagonitization were recovered from several intervals, and many of the samples contained fresh olivine. Altered intervals of the drill core show replacement of olivine and groundmass glass by green brown smectites, and the growth of smectites and carbonate in veins and vesicles. Detailed examination of thin sections, however, revealed that in several instances, the groundmass clinopyroxenes had also been partially replaced by smectite and that the plagioclases contain veins and patches of smectites growing along cleavage cracks and around the margins. The most intense alteration was seen in Core 50 from which two samples were collected. The lower sample, 474A-50-3, 103-106 cm, consists of a fine-grained, phryic, variolitic basalt containing approximately 10 modal percent plagioclase, olivine, clinopyroxene, and opaque, and smectite. The upper sample, 474A-50-2, 133-145 cm, is petrographically very similar, except for the fact that the clinopyroxene has been completely replaced by smectite.

Representative analyses of the smectites and carbonate are given in Table 3 and shown in Figure 2. Like the smectites from Hole 478 in the Guaymas Basin, they occupy a rather restricted range of relatively Mg-rich compositions compared to samples from other DSDP sites and show no evidence of increasing K₂O content with increasing total iron.

### Site 482

Site 482 was located approximately 12 km east of the East Pacific Rise in a sediment-filled valley south of the Tamayo Fracture Zone. The age of the crust is no greater than 0.5 m.y., and the sediment accumulation rates range between 340 and 550 m/m.y. A temperature of approximately 90°C was estimated for the basalt/sediment contact from shipboard measurements. Drilling at the site, however, opened a conduit through the sediments through which hot water flowed upward to form a small hot-spring on the ocean floor. The presence of this manmade spring was detected by temperature sensors in the Hawaiian downhole seismometer package which measured an equilibrium temperature of ~150°C near the bottom of Hole 482C. This clearly demonstrates that relatively high-temperature fluids are still circulating in the crust at Site 482 (Duennebier and Blackinton, 1980).

Basalts were successfully recovered from four of the holes drilled at Site 482. Several units could be correlated between holes on the basis of their lithologic, chemical, and magnetic properties. An upper aphyric unit which was 22 meters thick in Hole 482B, 24 meters thick in Hole 482C, and 29 meters thick in Hole 482D was underlain by a sequence of sparsely plagioclase-phyric basalts which were 18, 26, and 39 meters thick in Holes 482D, C, and B respectively. Farther down in the basement, thin cooling units predominate in all three holes. In addition, similar distributions of secondary minerals were seen in each of the holes. Pyrite, for example, is abundant just below the sediment/basement interface in all three holes. It is disseminated in the basalt groundmass and also occurs as vein and vesicle fillings. Veins of smectite, pyrite, and carbonate are particularly abundant. The abundance of the sulfides decreased rapidly down all three holes, only to reappear abruptly just below the next sediment/basalt interface.

In Section 482C-10-2, a large vein occurs in the upper 24 cm which splits a preexisting segregation vein. The vein has a prominent alteration halo and occurs in the same massive basalt unit as a patch of high-temperature secondary minerals. The sequence of minerals infilling this vein consists of finely disseminated sulfides, smectite and opal, pyrite, calcite, and barite. With the exception of the calcite (which is ubiquitous on the ocean floor), this is precisely the same mineral assemblage as that currently being discharged as particulate material from the group of active hydrothermal vents on the East Pacific Rise at 21°N known as the "white smokers." Temperatures of approximately 300°C were measured in these vents during the RISE expedition of 1979 (Haymon and Kastner, 1981). Paleotemperatures of this mag-

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**Table 3. Defocused microprobe analyses of smectites and carbonate, Hole 474A.**

<table>
<thead>
<tr>
<th>Oxide</th>
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<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>45.96</td>
<td>49.21</td>
<td>46.87</td>
<td>50.13</td>
<td>47.62</td>
<td>48.11</td>
<td>50.11</td>
<td>50.30</td>
<td>53.39</td>
<td>52.33</td>
<td>51.44</td>
<td>0.10</td>
</tr>
<tr>
<td>TiO₂</td>
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<td>0.12</td>
<td>—</td>
<td>0.12</td>
<td>—</td>
<td>0.32</td>
<td>0.11</td>
<td>0.04</td>
<td>0.02</td>
<td>—</td>
<td>0.10</td>
<td>—</td>
</tr>
<tr>
<td>Al₂O₃</td>
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<td>4.39</td>
<td>3.95</td>
<td>5.19</td>
<td>3.29</td>
<td>0.15</td>
<td>—</td>
<td>0.20</td>
<td>0.11</td>
<td>2.90</td>
<td>—</td>
</tr>
<tr>
<td>FeO**</td>
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<td>12.07</td>
<td>17.52</td>
<td>11.87</td>
<td>13.08</td>
<td>13.03</td>
<td>17.59</td>
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<tr>
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<td>0.10</td>
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<td>0.07</td>
<td>0.09</td>
<td>0.16</td>
<td>0.14</td>
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<tr>
<td>MgO</td>
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<td>18.91</td>
<td>17.52</td>
<td>11.87</td>
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<td>13.03</td>
<td>17.59</td>
<td>18.22</td>
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<tr>
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<td>0.72</td>
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<tr>
<td>Na₂O</td>
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<td>1.57</td>
<td>2.02</td>
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<td>0.34</td>
<td>0.18</td>
<td>0.50</td>
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<td>K₂O</td>
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<td>0.08</td>
<td>0.09</td>
<td>0.12</td>
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<tr>
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<td>87.78</td>
<td>89.24</td>
<td>88.65</td>
<td>90.64</td>
<td>55.55</td>
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</table>

**Note:** 1, groundmass smectite; Sample 474A-50-2, 133-135 cm; 2, green brown smectite around vesicle rim, Sample 474A-50-2, 133-135 cm; 3, smectite in center of same vesicle; 4, brown smectite around vesicle rim, Sample 474A-50-2, 133-135 cm; 5, smectite in center of same vesicle; 6, green smectite replacing groundmass plagioclase, Sample 474A-50-3, 103-106 cm; 7-10, smectites replacing olivines, Sample 474A-50-3, 103-106 cm; 11, groundmass smectite, Sample 474A-50-3, 103-106 cm; 12, carbonate in center of same vesicle as 2 and 3. Values shown in wt. %.
The smectites from Sample 482C-10-1, 16-18 cm, close to the large thermal vein in Core 482C, and in Sample 482B and D, respectively, were examined for the occurrence of greenoils, which would indicate high-temperature alteration. The smectites observed replacing groundmass pyroxenes compositionally similar to those seen in Holes 474A and 483, in Sample 482C-10-1, 16-18 cm, also show bulk compositional trends indicative of high-temperature alteration.

Outside the alteration halo associated with the hydrothermal vein in Core 482C-10, small patches of relic interstitial glass were found. The average composition of this glass is compared with that of the smectites replacing it in Table 5. If 1/P2O5 is taken as an index of fractional crystallization, then comparison of this glass with the bulk composition of the host basalt suggests that it represents the residue after approximately 70% solidification. Such glasses are rarely recovered unaltered from the ocean floor. Examination of Table 5 shows that the alteration of this interstitial glass involves an extensive loss of Si and Ca and a considerable gain in Mg. Potassium is also leached. These chemical changes are the same as those documented by Humphris and Thompson (1978) for the hydrothermal alteration of ocean floor basalts by seawater. In contrast, the low-temperature replacement of basaltic glass by palagonite typically involves an increase in K2O and a loss in Mg (Pritchard et al., 1979).

Site 483

Site 483 is located about 52 km west of the East Pacific Rise crest and about 25 km east of the base of the continental slope off Baja California. The basement structure is similar to that found at Sites 474 and 482—a sequence of interbedded sediments, massive flows, and pillow lavas, with the abundance of igneous rocks increasing downhole and good lateral correlation between adjacent holes. The calculated sedimentation rate (62 m/m.y.) is considerably lower than at the other sites.

At first glance the alteration of the basalts appears to be similar to that documented at the other sites. Pervasive alteration has resulted in the replacement of olivine and interstitial glass by smectites (Table 9) and minor carbonate. Veins and selvages are filled by, or partly altered to, smectite and carbonate. The amount of alteration increases downhole, but no systematic change was noted in grade of alteration. In addition, the groundmass and vesicles locally contain mixed precipitates of iron hydroxides and silica, indicating very strong oxidation (Table 10). Similar minerals resembling limonite in...
thin section have been reported from Atlantic basalts affected by low-temperature alteration by Humphris et al. (1980), who attributed the formation of limonite to the slow percolation of cold seawater through veins and vesicles containing sulfides. No sulfides were observed in the oxidized samples from Site 483.

Examination of Figure 2 shows that the smectites in the Site 483 basalts follow a totally different trend from those followed by the basalts from the other sites. Instead, they resemble the smectites described from Pacific and Atlantic basalts affected by low-temperature alteration in that they exhibit a strong increase in both K₂O and total iron. They also exhibit the widest range of FeO*/MgO ratios seen in the clay minerals from Legs 64 and 65.

Site 485

Site 485 was located approximately 12 km east of Site 482 on crust less than 1 m.y. old. The upper part of the basement consists of interlayered massive basalts and sediments. The massive basalts are similar to those found at Sites 482, 483, and 474 except that they are thicker and much more coarse grained. Most of the basalts again appear to exhibit low-temperature alteration characterized by the replacement of olivine and interstitial glass by smectite and minor carbonate. Nevertheless, it can be seen from Table 11 and Figure 2 that the smectites duplicate the trends shown by those from Sites 474 and 482 rather than Site 483. In addition, evidence for hydrothermal activity was noted in several sections of the core: Sample 485-17-2, 60-70 cm contains a hydrothermal breccia with fragments of basalt in a matrix of calcite. A vein of smectite containing small euhedral crystals of epidote occurs in Sample 485-24-1, 69-81 cm and minor amounts of actinolite and chlorite were reported replacing clinopyroxene, particularly in the lower part of the core.

BULK CHEMICAL CHANGES DURING ALTERATION

The main problem in documenting the effects of alteration on the chemistry of the basalts studied here consists in distinguishing these effects from primary differences in composition. Most of the basalts sampled were massive flows or sills which appear to have been considerably affected by in situ fractionation. Even within thin cooling units or pillows the problem cannot be entirely eradicated.

Glass–Basalt Comparisons

Figure 3 shows the major element variation exhibited by the glasses analyzed during the course of this study. Despite their extremely small range of MgO contents (less than 1 wt.%) the glasses exhibit two subparallel

Table 7. Microprobe analyses of sulfides, Site 482.

<table>
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<td>Fe₂O₃</td>
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<td>MgO</td>
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</tr>
<tr>
<td>Total</td>
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<td>94.97</td>
<td>99.64</td>
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Note: All analyses are of crystals from the center of a hydrothermal vein, Sample 482C-10-1, 16-18 cm.

Table 8. Microprobe analyses of barites, Hole 482C.

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<td>0.14</td>
<td>0.14</td>
<td>0.16</td>
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<tr>
<td>CaO</td>
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<td>0.14</td>
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<tr>
<td>SiO₂</td>
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</tr>
<tr>
<td>Al₂O₃</td>
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<td>0.14</td>
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<tr>
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<tr>
<td>K₂O</td>
<td>0.08</td>
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<td>0.14</td>
<td>0.16</td>
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<td>0.16</td>
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<tr>
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<td>95.67</td>
<td>94.97</td>
<td>99.64</td>
<td>100.69</td>
<td>101.39</td>
<td>100.92</td>
<td>98.07</td>
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</table>

Note: All analyses are of crystals from the center of a hydrothermal vein, Sample 482C-10-1, 16-18 cm.
trends. At any particular value of MgO, the glasses from Site 474 are richer in Al₂O₃, Na₂O, K₂O, and TiO₂ and poorer in total iron and CaO than the glasses from the other sites, reflecting their more alkalic nature. The single sample from Hole 477A is slightly offset from the 474A trend. With decreasing MgO, both trends show a regular decrease in CaO and Al₂O₃ and an increase in total iron, Na₂O, and TiO₂. It is tempting to explain these variations by the co-precipitation of olivine and plagioclase. Saunders (this volume) has shown that much of the major element variation between the different basalt units from Sites 474, 482, and 483 could be explained by such a mechanism, but that since the incompatible element variations cannot be entirely reconciled in this way, open magma chamber fractional crystallization may have been involved. A hint of this is revealed by the lack of correlation between K₂O and TiO₂ in Figure 3.

No such problems should be encountered, however, in comparing samples from the same eruptive unit. The two basalt samples from Hole 477A are both enriched in CaO and Al₂O₃ and depleted in all of the other major elements relative to the glass sample. Similar variations are seen in several, but not all, of the basalt-glass pairs studied from Hole 474A. Since these basalts are plagioclase-phyric, the simplest way of explaining these differences is to postulate variable accumulation of plagioclase phenocrysts. Similar compositional differences between basalt-glass pairs have been reported by Thompson (1980) for plagioclase-phyric samples recovered during Legs 51 through 53. The intraunit chemical variation revealed by a comparison of the remaining glass and basalt samples is less easy to reconcile by means of any kind of fractionation model and indicates that metamorphic processes have also been involved.

Examination of Tables 12 and 13 shows that all of the basalt-glass pairs from Site 482 (Samples 482B-14-1, 115-118 cm; 482D-10-3, 81-85 cm; 482D-10-3, 106-110 cm; 482D-11-2, 70-74 cm; and Samples 482D-14-1, 90-94 cm; 482D-10-3, 130-135 cm; 482D-10-3, 130-135 cm; and 482D-11-2, 33-38 cm in Tables 12 and 13, respectively) show enrichment of the basalts in Al₂O₃ and MgO and depletion in all of the other major elements, including CaO, relative to the glasses. The data could be explained if plagioclase fractionation was accompanied by high-temperature hydrothermal alteration. Some process involving plagioclase needs to be invoked to explain the Al₂O₃ variations since this element is little affected by alteration at either high or low temperatures.
High-temperature alteration of the basalts would both increase the MgO content and decrease the CaO content. Similar variations are shown by one of the basalt-glass pairs from Hole 474A (Samples 474A-46-3, 81-82 and 474A-46-2, 111-114 in Tables 12 and 13, respectively).

### Intraunit Variations

Samples of fresh glass were only available from a few of the cooling units. In the case of the other samples, most of which were from massive units, the nature of the chemical trends during alteration can only be determined by comparing samples from the same unit.
which show different degrees of alteration. Figure 4 shows selected minor and trace element data plotted against Zr for flows or sills from which multiple samples were collected. Examination of this figure shows that many of these units have been affected by considerable amounts of in situ fractional crystallization. This is clearly demonstrated by the covariation shown by Y, Zr, and TiO$_2$ in virtually all cases, since these elements are normally incompatible in basaltic liquids. The lack of correlation in several units between Sr and K$_2$O on the one hand and these elements on the other clearly suggests that Sr and K$_2$O were mobile, though the na-
Trends such as those shown in Figure 4 could in theory be the result of fractionation or accumulation shown by Ni and Zr in several of the units could easily be the result of fractionation or accumulation of olivine but could never be the result of the minor amounts of alteration shown by most of these samples; second, the fact that the most extensive variations are shown by the most massive units, such as the sills or...
flows from Holes 478 and 485A, and the tendency for the data from several units at one site to line up along the same trend, clearly support a fractionation mechanism.

Figure 4 was used to select those units which show little or no variation in the degree of alteration, the CaO, MgO, and K₂O contents of the resultant, very reduced sample set were plotted against loss on ignition as an index of alteration in an attempt to identify the processes responsible for the variations. Although several altered samples were thus excluded from
the data set, the results should still be typical of most of
the basalts because the secondary minerals at any one
site are similar in composition (Fig. 2). The results of
this exercise are shown in Figures 5 through 7. For pur-
poses of comparison, the changes shown by Humphris
and G. Thompson (1978) across individual pillows sub-
jected to hydrothermal alteration and the variations
produced during typical low-temperature alteration of
basalts by seawater (Pritchard et al., 1979) were also
plotted in the upper and lower right-hand diagrams,
respectively, of Figures 5, 6, and 7.

Figures 5 through 7 clearly demonstrate that the vari-
ations shown by the basalts from Sites 474 and 482
closely resemble those generated during high-tempera-
ture hydrothermal alteration of basalts by seawater—
i.e., a loss of CaO, increases in MgO, and little or no
change in K₂O. In contrast, the basalts from Site 483
show little or no systematic change in their CaO and
MgO contents as a result of increasing hydration, but do
show large variations in their K₂O contents—variations
typical of low-temperature alteration. It seems likely
that the samples from Site 485 were also affected by
hydrothermal alteration in view of the many similari-
ties in secondary minerals formed at Sites 474, 482, and 485.

CONCLUSIONS

The best way of explaining the findings outlined in
this chapter is to postulate that short-lived hydrother-
mal systems exist near the crest of the East Pacific Rise
and have existed in this region in the past. The layer-
cake nature of the oceanic crust in this area, i.e., inter-
digitated, laterally extensive layers of relatively imper-
meable sediments and more permeable basalts, make it
very unlikely that the fluids in these systems would have
penetrated more than a few basalt units at any one time.
The hydrothermal vein in the upper unit in Hole 482C
may well have been a vent for one of these small sys-
tems. Significantly, although Mooreby et al. (this vol-
ume) could find little evidence of Fe-enriched basal sedi-
ments in this region of the type found elsewhere along
the East Pacific Rise and Rise flanks, they did suggest

Table 13. Microprobe analyses of glasses, Legs 64 and 65.

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<td>49.67</td>
<td>49.96</td>
<td>50.09</td>
<td>50.76</td>
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<td>Al₂O₃</td>
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<td>15.15</td>
<td>15.52</td>
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<td>15.41</td>
<td>15.02</td>
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<td>TiO₂</td>
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Note: Each analysis listed represents a mean of 10 separate analyses. Values shown in wt.%. That some hydrothermally derived sulfide material may have been added to the sediments at Site 482.

The high sedimentation rates in the mouth of the
Gulf of California will cause any such systems to be very
short-lived, since fluid channels will be rapidly choked
by the influx of detrital material. Until the crust moves
away from the active spreading center and cools, some
circulation will still occur but the blanketing effect of
the overlying sediments will preclude any significant ex-
change with the seawater. Instead, the fluid composi-
tions will probably be buffered by the basalts, causing
the samples to retain a chemical fingerprint of the hy-
drothermal alteration which took place, even though the
greenschist-facies minerals will be gradually replaced by
species stable at lower temperatures.

The differences in the alteration mineralogy between
Site 483 and the other sites examined on Legs 64 and 65
can thus be explained by the lower sedimentation rate at
Site 483, which allowed seawater to have access to the
basalt for a longer period of time. Although the sedi-
mentation rate at Site 483 is high compared to that at
most other oceanic spreading centers, the sediment ac-
cumulation rates at the other sites investigated here were
an order of magnitude higher.

ACKNOWLEDGMENTS

We would like to thank the Leg 64 shipboard scientific party for
collecting samples from the core on our behalf. Considerable thanks
are also due to P. Suddaby and N. Wilkinson for their efforts in main-
taining the Imperial College microprobe system in peak operating con-
tdition and to P. Watkins for performing the FeO analyses. This work
was supported by the N.E.R.C. through Grant GR3/2946. The EDS
detector was provided by the N.E.R.C. through Grant GR3/3357.
The manuscript was improved as a result of critical comments from G.
L. Hendry.

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1285-1265.
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Figure 4. Variation of selected minor and trace elements versus Zr within basalt units drilled on Legs 64 and 65.
Figure 4. (Continued).
Figure 5. Variation of CaO with loss on ignition (LOI) in selected basalt units from Legs 64 and 65. (For explanation of right-hand diagrams see text.)
Figure 6. Variation of MgO with loss on ignition (LOI) in selected basalt units from Legs 64 and 65. (For explanation of right-hand diagrams see text.)
Figure 7. Variation of $K_2O$ with loss on ignition (LOI) in selected basalt units from Legs 64 and 65. (For explanation of right-hand diagrams see text.)