30. SECONDARY MINERALS IN BASALT FROM THE COSTA RICA RIFT, HOLES 501 AND 504B, DEEP SEA DRILLING PROJECT LEGS 68, 69, AND 70

Victor B. Kurnosov, Igor V. Kholodkevich, and Valerii M. Chubarov, Far-East Geological Institute, Vladivostok, U.S.S.R.
and

ABSTRACT

Basalt samples recovered during DSDP Legs 68, 69, and 70 from a 550-meter-thick section in two holes near the Costa Rica Rift (Holes 501 and 504B) were found to contain the following secondary minerals: trioctahedral and dioctahedral smectite, chlorite, mixed-layer clays, talc, hematite, pyrite, foujastite, phillipsite, analcime, nattrolite, thomsonite, gyrolite, aragonite, calcite, anhydrite, chalcanthite, Fe-hydrosilicate, okenite, apophyllite, actinolite, cristobalite, quartz, and magnesite. A less positive identification of bismuthite was made. A mineral rich in Mn and minerals with strong reflections at 12.9 Å and 3.20 Å remain unidentified.

Trioctahedral smectite replaces glass and olivine in the basalt groundmass. The other secondary minerals occur in veins. The distribution of the secondary minerals in the basalt section shows both hydrothermal and oxidizing-nonoxidizing zonation.

Most of the secondary minerals formed under alkaline, nonoxidizing conditions at temperatures up to 120°C. An acidic regime probably existed in the lowest portion of basalt. Oxidative diagenesis followed nonoxidative diagenesis in the upper part of the section. Oxidative diagenesis is characterized by the absence of celadonite, rare occurrences of dioctahedral smectite, and widespread hematite and phillipsite.

INTRODUCTION

Secondary minerals in basalts drilled from Holes 501 and 504B near the Costa Rica Rift were identified and analyzed, and an attempt was made to infer the physical and chemical conditions under which they formed.

METHODS

Secondary minerals were identified chiefly by X-ray diffraction analysis. Infrared spectral analysis, electron microscopy, scanning electron microscopy (SEM), and electron diffraction were also used. Chemical compositions were determined by wet chemical analysis and electron microprobe techniques. Secondary minerals in basalt groundmass were studied in the < 1 µm and 1 to 10 µm fractions.

SECONDARY MINERALS IN BASALT GROUNDMASS

Trioctahedral smectites are the principal secondary minerals in the basalt groundmass. Talc, which was found in Sample 504B-5-2, 142-146 cm, seems to have come from a thin veinlet. Minor chlorite was identified in the groundmass of basalt from Hole 501 only (Table 1).

Smectites, which formed by the alteration of interstitial glass and olivine, were identified by X-ray diffraction analysis in all samples studied. The basal reflection (001) varied from 3.6 to 15.2 Å, and the b-parameter varied from 9.8 to 9.21 Å (Sample 504B-7-2, 64-68 cm, 9.19 Å; 504B-24-1, 125-129 cm, 9.18 and 9.21 Å; 504B-70-1, 17-20 cm, 9.21 Å). As shown in Figure 1, the b-parameter suggests that the smectites are triocta-

---

Table 1. Occurrence of secondary minerals in basalt groundmass from Costa Rica Rift, Holes 501 and 504B, Legs 68, 69, and 70.

<table>
<thead>
<tr>
<th>Sample (interval in cm)</th>
<th>Sub-bottom Depth (m)</th>
<th>&lt; 1 µm</th>
<th>1 to 10 µm</th>
<th>Bulk</th>
<th>Chlorite</th>
</tr>
</thead>
<tbody>
<tr>
<td>501-10-2, 10-12</td>
<td>107.70</td>
<td>T</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-1, 74-77</td>
<td>100.30</td>
<td>T</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-1, 35-38</td>
<td>89.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-1, 126-128</td>
<td>70.30</td>
<td>T</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20, 19-41</td>
<td>65.80</td>
<td>T</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>504B-3-1, 96-99</td>
<td>76.80</td>
<td>T</td>
<td>T</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

<sup>1</sup> Unpublished Data. A Trace denotes trace. 
<sup>2</sup> Trace of talc(?)

---

The saponites consist of isometric fragments of different size and thickness (Plate 1, Fig. 1) or (rarely) elongated lamellae and needles.

Chemical analysis of the < 1 μm fraction derived from basalt shows that the saponite is a low-K Fe-Mg-saponite (Table 2). The composition of the groundmass saponite changes slightly through the basalt section. From about 470 meters sub-bottom (Sample 504B-27-2, 55-58 cm) downward, the saponite decreases in MgO and increases in CaO and Na2O content. The very lowest sample (Sample 504B-70-1) has high levels of Fe2O3 and Fe3O4 + FeO and the lowest K2O content.

Chemical analysis shows that the < 1 μm fraction does not consist entirely of saponite; this fraction also contains plagioclase and volcanic glass.

MINERALS IN VEINS AND VESICLES

The following minerals were identified in basalt veins and vesicles: saponite, Fe-smectite, chlorite, talc, mixed-layer minerals, hematite, pyrite, phillipsite, foujaisite, analcime, natrolite, thomsonite, gyrolite, aragonite, calcite, anhydrite, Fe-hydroxide, chalcocite, okenite, apophyllite, actinolite, cristobalite, quartz, bismuthite(?), and magnesite (Table 3). A mineral rich in Mn and minerals with strong reflections at 12.9 Å and 3.20 Å could not be identified.

Clay Minerals

Clays from the veins and vesicles are triohedral smectites (saponites) of diverse color—black and dark green, gray, dark green with a silk luster, light green, yellow brown, and red brown (Fig. 1). The b-parameter of these clays ranges from 9.18 to 9.23 Å. Minor dioctahedral smectite (b = 9.02, 9.04, and 9.06 Å) was found in the light green, yellow brown, and red brown clays.

The black and dark green clays in the veins are low-K Fe-Mg-saponites (Table 4). The MgO content of these varieties ranges from 12 to 20%, the Fe2O3 + FeO content from 10 to 17%. Most particles are isotropic in form, but some lath-shaped fragments were identified in

![Figure 1. b-parameter of clays from veins and basalt groundmass, Hole 504B, Costa Rica Rift, Legs 69 and 70, plotted versus depth below the seafloor.](image-url)
Sample 504B-29-1, 31-34 cm. The structure of smectite in black clay is shown in Tables 2 and 4.

Analyses were made of green saponite clays that occur as globules in veins in Samples 501-15-1, 109-111 cm and 504B-16-1, 45-49 cm. The clays are saponites with a content of MgO up to 22% and a maximum K$_2$O content of 0.33% (Table 5). Black clay located along the walls of a vein in Sample 501-15-1, 109-111 cm has higher iron and alumina contents, lower magnesium content, and significantly higher K$_2$O content (2.4%) (Table 5).

Green clays in veins from the zeolite zone (Samples 504B-34-2, 18-21 cm; 504B-35-2, 14-16 cm; and 504B-38-1, 7-15 cm) were also studied. In Sample 504B-34-2, 18-21 cm a brecciated glassy crust is composed of fine blocks of glass altered to smectite. These blocks consist of dark green saponite with 18% MgO and 0.63% K$_2$O (Table 5). The centers of the blocks consist of lighter green Fe-Mg-saponite with 4.17% K$_2$O. In the same sample there is a white smectite vein at the glassy crust/basalt contact. Its chemical composition is as follows: SiO$_2$, 50.13; TiO$_2$, 0.01; Al$_2$O$_3$, 8.93; FeO, 6.26 (total Fe as FeO); MnO, 0.17; MgO, 19.83; CaO, 1.25; Na$_2$O, 0.94; K$_2$O, 1.12%; total, 88.64%.

In Sample 504B-35-2, 14-16 cm, first green and then dark green (Fe-MgO-saponite) clays occur as one proceeds from the central part of a vein (which consists of
natrolite and calcite) toward basalt. Of the two clays, the dark green clay is richer in K$_2$O (4.48%) and Na$_2$O (1.46%) (Table 5). The green clay has higher alumina and iron contents, slightly lower MgO content, and lower K$_2$O (1.91%) and Na$_2$O (0.42%) content.

In Sample 504B-38-1, 7–15 cm, green clay occurs in association with analcime, calcite, and gyrolite. It consists of Fe–Mg–saponite with a K$_2$O content of 0.60% (Table 5).

The gray clay is another Fe–Mg–saponite with low K$_2$O content (0.20%). MgO content is 21.23%, and Fe$_2$O$_3$ content is 4.55% (Table 4). Particles are lath shaped or ribbonlike (Plate 1, Fig. 2). Under the scanning electron microscope, the gray clay shows a rosette texture (Plate 2, Figs. 1 and 2). Traces of chlorite were also identified in this clay (Samples 504B-15-1, 19–1 cm and 21–2 cm).

The dark green clay with a silk luster is also saponite with lath-shaped particles. Its natural texture is shown in Plate 2, Figure 3.

The yellow brown clay is similar to the light green clay.

The red brown clay consists of saponite and finely dispersed hematite, with traces of dioctahedral Fe–smectite (b-parameter, up to 9.06 Å). The clay particles are isometric in shape (Plate 1, Fig. 4).

A comparison of the chemical composition of the clay minerals in the veins and basalt groundmass shows that the clay minerals in the veins are usually higher in MgO, lower in Fe$_2$O$_3$ and Al$_2$O$_3$, and sometimes higher in K$_2$O (Samples 504B-5-2, 504B-10-3, 504B-29-1, and 504B-61-1). Light green clay in a vein in the oxidized zone (Sample 504B-5-2) is not distinguished by its chemical composition.

**Other Minerals**

All the secondary nonclay minerals that were found are enumerated in the preceding material. They were identified by X-ray diffraction analysis (Joint Committee on Powder Diffraction Standards, 1974).

The unknown mineral rich in Mn in Sample 501-10-2, 10–12 cm was also analyzed by microprobe techniques (Table 6). The centrum part of the mineral contains 19.84% MnO (P-trace) and 2.53% MgO. Narrow zones analogous in composition to the central part of the min-

---

### Table 4. Chemical composition (wt.%) of saponites from clay veins of basalt from the Costa Rica Rift, Legs 69 and 70.

<table>
<thead>
<tr>
<th>Sample (interval in cm)</th>
<th>504B-5-2</th>
<th>504B-10-3</th>
<th>504B-16-1</th>
<th>504B-32-2</th>
<th>504B-34-2</th>
<th>504B-38-2</th>
<th>504B-49-1</th>
<th>504B-61-1</th>
<th>504B-70-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Light Green</td>
<td>Gray</td>
<td>Light Green</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
<td>47.20</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>MgO</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>CaO</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
</tr>
<tr>
<td>LOI</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
<td>19.84</td>
</tr>
</tbody>
</table>

---

### Table 5. Chemical composition of clay minerals from veins of basalt, Costa Rica Rift, Legs 68, 69, and 70.

<table>
<thead>
<tr>
<th>Sample (interval in cm)</th>
<th>501-15-1</th>
<th>501-15-1</th>
<th>504B-16-1</th>
<th>504B-16-1</th>
<th>504B-34-2</th>
<th>504B-34-2</th>
<th>504B-35-2</th>
<th>504B-38-2</th>
<th>504B-38-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color of Clay</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
</tr>
<tr>
<td>Component</td>
<td>Light Green</td>
<td>Gray</td>
<td>Light Green</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
<td>44.66</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
<td>3.34</td>
</tr>
<tr>
<td>MgO</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>CaO</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
<td>12.56</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>LOI</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
<td>11.76</td>
</tr>
<tr>
<td>Total</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
<td>99.74</td>
</tr>
</tbody>
</table>

---

*a* Loss on ignition.
eral alternate with zones containing about 4% MnO and up to about 23% MgO, with higher Al₂O₃, SiO₂, FeO, Na₂O, and K₂O contents and much lower CaO contents (to 2.73%). We failed to identify the Mn-rich mineral.

Chalcocite was identified in Sample 504B-35-2, 14-16 cm from microprobe data. Weak 3.76, 2.94, and 2.13 Å reflections in clay from Sample 504B-3-1, 94-96 cm were attributed to bismutite.

The results of microprobe analyses of analcime and natrolite are given in Table 7. Natrolite has a high K₂O content (up to 5%). Part of a vein in another sample is milk white, and the chemical composition of this part of the vein, which according to X-ray diffraction analysis consists of analcime (5.57, 3.42, and 2.92 Å), calcite (3.03 Å), and an unidentified mineral with a strong reflection at 12.9 Å, is shown in Table 8. The CaO content of this part of the vein is high (up to 24.49%). It is possible that the 3.03 Å reflection attributed to calcite actually belongs to the mineral with the strong reflection at 12.9 Å. This mineral appears to be in an isomorphous mixture with analcime. The chemical composition of the gray part of the same vein is also shown in Table 8.

Okenite was identified from its 19.6 Å reflection in material from an analcime-filled vein in Sample 504B-35-1, 70-72 cm.

An unidentified mineral with a strong reflection at 3.20 Å (possibly faechildite) was found in Samples 501-10-2, 10-12 cm, from basalt of Costa Rica Rift, Leg 68.

Vein foujasite (identified by a strong reflection at 14.25 Å) was found in Sample 501-15-1, 109-111 cm together with phillipsite. The chemical composition of foujasite is shown together with that of phillipsite in Table 7. Fe-hydrosilicate (Table 9) was detected in the same sample by microprobe analysis.

A red ferruginous film found in Sample 504B-18-1, 45-49 cm was studied by X ray. Hematite was identified by its 3.65, 2.70, 2.50, 2.20, 1.83, and 1.68 Å reflections.
Vein minerals identified in the Costa Rica Rift basalts occur in the following principal associations: black clay + hematite ± light green clay and phillipsite; black clay + pyrite; black clay + gray clay ± phillipsite; black clay + aragonite; black clay + analcime + other Ca-, Na-, and K-minerals; black clay + anhydrite + quartz ± apophyllite; and green clay in pores.

Black clay is widespread, present in thin veins through the whole basalt section. Thick layers of black clay were found mainly in brecciated glassy crusts. Hematite and pyrite divide the basalt into two significant parts: an interval with hematite from 278 to 570 meters sub-bottom and an interval with pyrite from 570 to 827 meters sub-bottom. Light green clay, which occurs as thin, 1-mm-thick layers that cover the black clay, is present mainly to a depth of 570 meters sub-bottom.

The vein mineral assemblages can be used to divide the interval from 278 to 570 meters sub-bottom into three parts in turn: from 278 to 427 meters sub-bottom, 427 to 570 meters sub-bottom, and 570 to 827 meters sub-bottom.

Gray clay occurs at depths up to 427 meters sub-bottom. It exists as shapeless lumps and clearly outlined fragments and occurs mainly in brecciated glassy crusts. It also occurs in veins up to 1 cm wide with black clay, dark green clay with a silt luster, and phillipsite (Plate 2, Figs. 4 and 5). The contact between gray and black clays is distinct and metasomatic. Bismutite(?), actinolite, and chlorite were identified in the gray clay. In the same part of the basalt section (to a depth of 427 meters sub-bottom) black clay lines veins that are filled with aragonite. In this part of the section talc, thomsonite, cristobalite, a mineral rich in Mn, foujasite, Fe-hydrosilicate, magnesite, and a mineral with a reflection at 3.20 Å were also detected.

In the interval from 427 to 570 meters sub-bottom hematite and phillipsite were identified in veins lined with black clay.

In the interval from 527 to 570 meters sub-bottom the black clay lines veins that are filled mainly with analcime. Natrolite, okenite, gyrolite, calcite, phillipsite, chalcocite, chlorite, and an unidentified 12.9 Å mineral were also found in association with the analcime. These veins occur mainly in the glassy crusts and brecciated glass.

Pyrite is a common mineral in the interval from 570 to 827 meters sub-bottom, where it is associated with black clay. A zone within this interval (751 to 809 meters sub-bottom) has veins that consist of anhydrite and quartz and have black smectite linings. Apophyllite was found in association with anhydrite in Sample 504B-61-1, 55-60 cm.

Pores filled with green clay are present all through the basalt section. To a depth of 527 meters sub-bottom, the clay is light green in color; below that depth it is darker. In Sample 504B-32-2, phillipsite was found in pores with the clay. The texture of smectite in a pore is shown in Plate 2, Figure 6.
Temperature measurements near the base of Hole 504B (Becker et al., this volume) indicate that the highest temperature of formation of the secondary minerals in the Costa Rica Rift basalts did not exceed 120°C. The temperature measured at the sediment/basalt contact is about 60°C. Where smectites are present their temperature of formation can be inferred from the temperature of formation of the rest of the mineral assemblage. This temperature ranges from a high of about 100°C (where the smectite is associated with anhydrite and quartz) to a low of about 25°C (where the smectite is associated with hematite, cristobalite, pyrite, and phillipsite). The low temperature smectites are black clay, which occurs in the basalt groundmass and veins and formed during the initial stages of basalt heating, and light green and red brown clays, which were produced by oxidative diagenesis. The idea that the light green and red brown clays (as well as the black clays) formed at about 25°C is advanced by Seyfried et al. (1976 and 1978).

**SOURCES OF MATERIAL**

Experiments on basalt/seawater interaction (Bischoff and Dickson, 1975; Kotov et al., 1978; Mottl and Holland, 1978; Mottl et al., 1979; Kholodkevich et al., 1981) show that glassy tholeiitic basalt has all the components necessary for the formation of the secondary minerals identified in the Costa Rica Rift basalts. However, some endogenous components are also present in the Costa Rica Rift basalts (fluorine and potassium in apophyllite; sulfur in anhydrite, pyrite, and chalcopyrite; and CO₂ in aragonite). Some of the secondary mineral cations also appear to be endogenous, especially in the lower part of the basalt section.

**HISTORY OF SECONDARY MINERAL FORMATION**

Pillow lava and submarine flows typically go through a deuteric stage of alteration and halmyrolysis and then reheat as basalts pile up. In the pillow lavas of the Costa Rica Rift, the deuteric stage and halmyrolysis did not produce secondary minerals (or at least none that have survived subsequent alteration). Studies of certain oceanic basalts (Kurnosov et al., 1978) show that secondary minerals do not necessarily form in glassy crusts in the deuteric stage or during long contact with cool sea water (halmyrolysis). Furthermore, no minerals formed in the pillow lava glassy crusts during the deuteric stage of halmyrolysis under oxidizing conditions. This observation disagrees with Bass’s (1976) view that oxidative diagenesis occurs during the initial stages of basalt cooling.

The deuteric stage may however be of great importance for the formation of secondary minerals in the sills and thick flows (tens of meters) when seawater penetrates the solidifying lava slowly. Such deuteric minerals were reported in the Nauru Basin basalts recovered during Leg 61 (Kurnosov et al., 1981).

The secondary minerals in the Costa Rica Rift basalts formed later, while the basalts were being reheated. The reheating was rapid because this zone is relatively hot (the temperature measured at the sediment/basalt contact in the Hole 504B was about 60°C [Becker et al., this volume]). Early during this reheating, while temperatures were still relatively low, saponite grew in fractures and pores, replaced basalt groundmass material, and fragmented glassy crusts. Material for the formation of saponite was produced by basalt/seawater interaction.

A further increase in temperature toward the lower part of the section resulted in vein mineralization, with three assemblages appearing from the base upward: anhydrite-quartz with apophyllite; zeolite; and aragonite. Gray clay veins formed within the aragonite zone. The black clay that comprises the vein linings formed at higher temperatures than the black clay that formed during the first stages of the reheating of the basalt. Low temperature saponite clay remained stable during the temperature increase.

The mineral zones identified reflect the temperature facies of hydrothermal alteration. The source of F, CO₂, and part of the S, as well as a number of cations, such as K in apophyllite, was endogenous.

The appearance of such high temperature minerals as talc, actinolite, and chlorite in the upper part of the section breaks the temperature zonation. Bismutite, which experiments have shown to form at 400-500°C (Mottl and Holland, 1978), was identified in the same part of the section.

The occurrence of these high temperature minerals in an otherwise low temperature zone can be explained by the different degree of saturation of the solutions with cations in the upper and lower parts of the basalt. With a sufficient degree of saturation temperature need not be so high.

The second type of zonation identified in the Costa Rica Rift basalts, which is based on the distribution of pyrite and hematite in the section, corresponds to the transition from nonoxidizing to oxidizing conditions. This boundary lies approximately 570 meters below the seafloor and 300 meters below the sediment/basalt interface. Oxidative diagenesis occurred during the final stage of secondary mineral formation, when tectonic movements caused old fractures to reopen and new ones to originate. New seawater, rich in oxygen, penetrated these fractures. Oxidative diagenesis manifested itself by the appearance of hematite, which was followed by the formation of phillipsite and of red brown, light green, and yellow brown clays. These rare minerals, which form under oxidizing conditions, are superposed on all other mineral assemblages to a sub-bottom depth of 570 meters.

The participants in Legs 69 and 70 noted both normal and reverse zonation in the distribution of clays in basalt veins. This can be accounted for not only by pH behavior but by the reopening of previously healed fractures. The rarity of hematite, phillipsite, and light green and yellow brown clays in the basalt section results from the fact that old fractures did not reopen everywhere.

The minerals that result from oxidative diagenesis in the Costa Rica Rift differ from those identified in some other mid-ocean ridges (Bass, 1976; Robinson et al., 1977) in that potassium is present in phillipsite instead of celadonite and nearly all Fe³⁺ is fixed in hematite.

A comparison of secondary minerals and the conditions of their formation in the Cretaceous off-ridge mafic complex of the Nauru Basin (Kurnosov et al., 1981)
with the Cenozoic pillow lavas of the Costa Rica Rift shows that the lava eruption mechanism determines the timing of the initial stage of secondary mineral formation in basalts and the composition of the resulting minerals. The eruption of thick flows and the intrusion of sills during Nauru Basin magmatism were immediately followed by the formation of secondary minerals—that is, the minerals formed during the deuteric stage. Where thin flows and pillow lavas have erupted, secondary minerals do not form in the deuteric stage but begin to originate during a later stage of heating. Therefore, during the formation of off-ridge basement in Cretaceous Nauru Basin (Shcheka, 1981; Shcheka and Kurenzova, in press), the conditions of secondary mineral formation and those of cation flux into the ocean and sediments were probably different from those at the Costa Rica Rift.

CONCLUSIONS

Secondary minerals in tholeiitic basalts of the Costa Rica Rift were formed by seawater/basalt interaction and endogenous element addition during the heating of the pillow lavas. The secondary minerals formed mainly under reducing alkaline conditions over a wide temperature interval. An acidic regime for secondary mineral formation was identified in the lower parts of the section.

Two types of zonation in vein mineralization were identified in the distribution of the secondary minerals in the basalt section: hydrothermal zonation and oxidative-nonoxidative zonation.

An interesting phenomenon is the occurrence of high temperature minerals in the upper part of the section and their absence in the lower part. We explain this by the different degree of saturation of the solutions with dissolved cations in the upper and lower parts of the basalt section.

Oxidative diagenesis manifested itself in the final stages of secondary mineral formation to a sub-bottom depth of 300 meters. The oxidative mineral assemblages differ from those known in some other portions of the mid-ocean ridges in the absence of celadonite and the presence of phillipsite. The minerals formed during this stage of alteration are less abundant than those formed under nonoxidizing conditions in the Costa Rica Rift.

ACKNOWLEDGMENTS

We thank Dr. P. Robinson and Dr. E. Leikov for reviewing the manuscript, and T. Bortina, G. Yudina, N. Ryapolova, V. Piskunova, and L. Kovbas for analytical work and helping to put the manuscript into shape.

REFERENCES


Plate 1. Electron micrographs of saponites from Leg 69 and 70 basalts. 1. Saponite from basalt groundmass, × 8000; Sample 504B-70-1, 17-20 cm (size is <2 µm). 2 to 4. Saponite from veins. (2) Gray clay. Sample 504B-10-3, 17-20 cm; × 7000. (3) Light green clay. Sample 504B-5-2, 142-146 cm; × 7000. (4) Red brown clay. Sample 504B-2-1, 108-110 cm; × 12,000.
Plate 2. Electron micrographs of minerals from Leg 69 and 70 basalts. 1. Gray clay, × 300; Sample 504B-7-2, 64–68 cm. 2. Gray clay in basalt, × 500; Sample 504B-9-1, 142–147 cm. 3. Dark green clay with a silk luster, × 300; Sample 504B-10-3, 17–20 cm. 4. Phillipsite on the gray clay, × 300; Sample 504B-9-1, 142–147 cm. 5. Same sample, × 3000. 6. Smectite(?) in basalt, × 1500; Sample 504B-37-1, 55–60 cm.
Plate 3. Electron micrographs of minerals from Leg 69 and 70 basalts. 1. Vein aragonite in basalt, × 50; Sample 501-15-3, 134-136 cm. 2. Same sample, × 1500. 3. Pyrite in black clay, × 4500; Sample 504B-61-2, 145-149 cm. 4. Pyrite in black clay, × 5000; Sample 504B-70-1, 17-20 cm. 5. Nondetermined sphere on the pyrite, × 300; Sample 504B-61-1, 55-60 cm. 6. Same sample, × 1000.