6. MINERAL PARAGENESIS OF ALTERED BASALTS FROM HOLE 504B, ODP LEG 111¹

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ABSTRACT

Basalts recovered from Hole 504B during ODP Leg 111 are more or less altered, but there is no sign of strong shear stress or widespread penetrative deformation; hence, they retain well their primary (igneous) structures and textures. The effect of alteration is recognized as the partial or total replacement of primary minerals (olivine, clinopyroxene, and plagioclase) by secondary minerals and as the development of secondary minerals in open spaces (e.g., veins, fractures, vugs, or breccia matrix). The secondary minerals include zeolite (laumontite and stilbite), prehnite, chlorite, epidote, plagioclase (albite and/or oligoclase), amphibole (anthophyllite, cummingtonite, actinolite, and hornblende), so-dic augite, sphene, talc, anhydrite, chalcopyrite, Fe-Ti oxide, and quartz. Selected secondary minerals from several tens of samples were analyzed by means of an electron-probe microanalyzer; the results are presented along with brief considerations of their compositional features.

In terms of the model basaltic system, the following two types of low-variance (three-phase) mineral assemblages were observed: prehnite-epidote-laumontite and prehnite-actinolite-epidote; both include chlorite, albite and/or oligoclase, sphene, and quartz. The mineral parageneses delineated by these low-variance mineral assemblages suggest that the metamorphic grade ranges from the zeolite facies to the prehnite-actinolite facies. The common occurrence of prehnite indicates that greenschist facies conditions were not attained even in the deepest level of Hole 504B, which, in a strict sense, contradicts the previous interpretation that the lower portion of Hole 504B suffered greenschist facies alteration.

INTRODUCTION

Since Matthews et al. (1965) reported metamorphosed basalts dredged on the crest of the Carlsberg Ridge, the mid-ocean ridge in the northwestern Indian Ocean, occurrences of metamorphic rocks have been increasingly recognized from the ocean floor around the world. Particularly, petrologic studies of metamorphic rocks obtained from the ocean floor have thrown new light on the metamorphic processes taking place near divergent plate boundaries (Melson and van Andel, 1966; Cann and Funnell, 1967; Cann, 1969; Ploshko et al., 1970; Miyashiro et al., 1971; Aumento et al., 1971; Bonatti et al., 1975; Helmstaedt, 1977; Ito and Anderson, 1983; Honnorez et al., 1984; Alt et al., 1986). Miyashiro et al. (1971) called it "ocean-floor metamorphism." However, the majority of these studies dealt with dredged samples, for which the detailed metamorphic sequence of oceanic crust is not well known. Drilled samples are more suitable for understanding the sequential nature of ocean-floor metamorphism, because they represent a relatively continuous section of oceanic crust.

Hole 504B, located in 5.9-Ma-old oceanic crust at 3460 m below sea level about 200 km south of the Costa Rica Rift, was cored and logged during parts of Legs 69, 70, 83, and 92 of the Deep Sea Drilling Project (DSDP). Coring during these legs to 1350 m below seafloor (mbsf) (1075.5 m into basement) consisted of 274.5 m of sediment and then 571.5 m of pillow lavas and minor flows, underlain by a 209-m-thick zone of transition into 295 m of sheeted dikes and massive units. Leg 111 of the Ocean Drilling Program (ODP) further deepened Hole 504B by 212.3 m, to a total depth of 1562.3 mbsf (1287.8 m into basement). Hole 504B thus provides an excellent opportunity for understanding the nature of metamorphism of the oceanic crust. The following is a petrological description of the basalts recovered from Hole 504B during ODP Leg 111, along with a discussion of their mineral parageneses.

PETROGRAPHY

Precursor Basalts

The basalts recovered from Hole 504B during ODP Leg 111 represent a 212.3-m section of the oceanic crust ranging in depth from 1350 to 1562.3 mbsf, or from 1075.5 to 1287.8 m into basement. Chilled intrusive contacts are distinct in several portions of the cores, suggesting that the basalts are all from massive dike units. At or near the chilled intrusive contacts, there are breccias (so-called chilled marginal breccias) composed of angular and glassy fragments cemented in a fine-grained basaltic matrix. The basalts are more or less altered, but they lack evidence of strong shear stress or widespread penetrative deformation. Hence, their primary (igneous) structures as well as textures can be recognized, and the first classification of rock type is into aphyric and phyric basalts, of which the former comprises one-third of the examined samples. There is no sign of vesiculation, although irregular millimeter-sized vugs are present both in the aphyric and phyric basalts.

The aphyric basalts include essentially no phenocrysts; for practical purposes they contain less than 1% phenocrysts. They are fine to medium in grain size and are composed of olivine, clinopyroxene, and plagioclase with minor Fe-Ti oxide. Subophitic texture dominates the medium-grained aphyric rocks, but the fine-grained varieties exhibit intergranular texture. In contrast, the phyric basalts have a texture in which more than 1% phenocrysts are set within a crystalline or glassy groundmass. They are composed of olivine, clinopyroxene, plagioclase, Crspinel, and Fe-Ti oxide, of which the Cr-spinel is found as inclusions in olivine and/or plagioclase phenocrysts whereas the other phases comprise both phenocrysts and groundmass with various combinations. The groundmass of the phyric basalts ranges in grain size from glassy to medium grained and displays subophitic to intergranular texture.

¹ Becker, K., Sakai, H., et al., 1989. Proc. ODP, Sci. Results, 111: College Station, TX (Ocean Drilling Program).

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Alteration

Alteration was described in the present study from 48 thin sections. The primary and secondary minerals found in the thin sections are listed in Table 1.

Both the aphyric and phyric basalts examined here are generally moderately altered (about 10%-30% recrystallized). The degree of alteration appears to be higher in fine-grained rocks than in medium-grained ones, although the glassy materials are generally less altered. The effect of alteration is recognized as partial or total replacement of primary (igneous) phases by secondary minerals and as development of secondary minerals in open spaces (e.g., veins, fractures, vugs, or breccia matrix), which is summarized in the following.

Olivine

Dark green to dark brown pseudomorphs after olivine phenocrysts as well as groundmass olivine are well recognized by a characteristic olivine crystal form, and some pseudomorphs after olivine phenocrysts include a tiny euhedral and unaltered Crspinel (Fig. 1A). Secondary minerals found in olivine pseudomorphs are amphibole, chlorite with or without mixed-layer clay, talc, quartz, sulfides (pyrite and chalcopyrite), and secondary magnetite. Locally (e.g., Sample 111-504B-142R-1, 2-4 cm) olivine retains its primary composition, but its margin and irregular cracks are altered to talc and chlorite.

Clinopyroxene

Among the constituent primary minerals, clinopyroxene is the least altered mineral. Secondary minerals are restricted to the margin around or cracks within clinopyroxene phenocrysts (Fig. 1B), whereas some of the groundmass clinopyroxene is totally altered. Chlorite and/or amphibole are the most common secondary minerals replacing clinopyroxene both in phenocrysts and groundmass.

Plagioclase

In both phenocrysts and groundmass, plagioclase is partially altered to sodium-rich plagioclase (albite and/or oligoclase), prehnite, zeolite, and chlorite. In Sample 111-504B-142R-1, 118-121 cm, a single phenocryst of plagioclase is totally replaced both by prehnite and zeolite (stilbite) (Fig. 1C). Anhydrite was rarely found partly replacing plagioclase phenocrysts (Fig. 1D). Glass inclusions, some of which are aligned parallel to twin planes of large plagioclase phenocrysts, are generally altered to chlorite and/or mixed-layer clay.

Veins, Fractures, Vugs, and Breccia Matrix

Besides the secondary minerals associated with the primary phases previously described, veins or fractures or vugs that commonly occur in varying abundance both in the aphyric and phyric basalts also include various kinds of secondary minerals such as prehnite, chlorite, amphibole, epidote, and zeolite. All of these secondary minerals do not coexist. Monomineralic (generally chlorite) veins or fractures are also abundant. The mineral associations observed in the veins or fractures or vugs including more than two phases are as follows: prehnite, prehnite + amphibole (Fig. 2A), prehnite + amphibole + epidote (Fig. 2B), prehnite + epidote + zeolite (Fig. 2C), and prehnite + amphibole + zeolite, all including chlorite, sphene, and Fe-Ti oxide with or without albite and/or oligoclase and quartz. Of these, the amphibole-zeolite association has the textural relationship showing that the amphibole develops as needlelike crystals scattered within the zeolite grain. This may represent a disequilibrium relationship between amphibole and zeolite. Sodic augite-bearing veins also occur together with chlorite, zeolite, and prehnite (Fig. 2D). The breccia matrix is extremely altered (50%-100% recrystallized) to amphibole, chlorite, prehnite, zeolite, and albite with disseminated sphene, in which the amphibole and zeolite also show the same textural relationship as previously described. Locally (e.g., Sample 111-504B-159R-1, 52-56 cm) a completely altered patch, ranging from 0.5 mm to 1.0 cm in diameter, occurs both in aphyric and phyric basalts, in which clinopyroxene is completely altered to needlelike to prismatic amphibole with minor chlorite.

MINERALOGY OF SECONDARY MINERALS

Before dealing with the mineral paragenesis, the chemistry and mode of occurrence of selected secondary minerals are described in this section. The analyses were performed using a JEOL Model JXA-733 electron-probe microanalyzer with a wavelength-dispersive analytical system (WDS) at the National Institute of Polar Research (Tokyo). Supplementary microprobe analyses were done using a Hitachi Model S-550 scanning electron microscope with a Kevex energy-dispersive analytical system (EDS), at Kyoto University, and a JEOL Model JXA-733 with WDS, at the Ocean Research Institute (University of Tokyo).

In total, 32 polished thin sections were analyzed, and the mineral assemblages are given in Table 1. The chemical nature of selected secondary minerals is summarized in Table 2, and representative analyses are listed in Tables 3 to 9.

Zeolites

Analyzed zeolites (Table 3) are identified as laumontite and stilbite. The laumontite is commonly found as discrete patches in veins, fractures, vugs, and breccia matrix, and some occurs as partially replacing primary plagioclase. The stilbite is generally restricted to a partial replacement of primary plagioclase, but in Sample 111-504B-149R-2, 50-53 cm, it fills a vein as platy crystals. There is, however, no association of laumontite + stilbite (1) in a single vein or fracture or vug or (2) in a replacement of a single primary plagioclase crystal.

Compositionally, the zeolites are commonly homogeneous, approaching the ideal stoichiometry of laumontite and stilbite, respectively, even though some small amounts of Na₂O are contained in laumontite (up to 0.66 wt%) and stilbite (up to 0.29 wt%).

Prehnite

Prehnite (Table 4) occurs mainly as discrete patches in veins, fractures, vugs, and breccia matrix or as fine-grained aggregates after plagioclase phenocrysts. Some anhedral platy prehnite appears as homogeneous crystal aggregates in veins. Rarely, prehnite with rotatory extinction between crossed nicols is found partially replacing primary plagioclase.

The frequency distribution of XFe = $Fe^{3+}/(Fe^{3+} + Al)$ of prehnite is illustrated in Figure 3. Compositionally, besides the major oxides (SiO₂, Al₂O₃, and CaO), the prehnites contain a significant amount of $Fe_2O_3^*$, up to 7.9 wt%. The XFe content was found to be apparently higher in prehnite associated with laumontite + epidote than in that with actinolite + epidote.

Chlorite

Chlorite (Table 5) is the most common secondary mineral, occurring in veins, fractures, vugs, and breccia matrix. Chlorite also occurs as partially to totally replacing primary olivine, clinopyroxene, and plagioclase; it commonly takes the form of fine-grained aggregates, but some shows an anhedral platy form.

The compositional variation of chlorite in terms of Al-Fe-Mg is illustrated in Figure 4. There is a slight compositional difference in relation to mode of occurrence; for example, the most magnesian chlorite occurs within olivine pseudomorphs whereas the most aluminous one occurs along the cracks of plagioclase phenocrysts. In spite of this slight compositional difference, the

Table 1. Mineral associations, Hole 504B, ODP Leg 111.

Core, section, interval (cm)	Depth (mbsf)	Primary clino- pyroxene	Primary plagioclase	Primary spinel	Olivine pseudo- morph	Amphibole	Epidote	Chlorite	Prehnite	Zeolite	Meta- morphic plagioclase	Quartz	Sphene	Anhydrite/ metamorphic clinopyroxene ^a (sodic augite)
^b 142R-1, 2-4	1352.8	+	+	+	+	+		+					+	
142R-1, 2-4	1352.8	+	+		+			+						
^b 142R-1, 118-121	1354.0	+	+		+	+	+	+	+	+	+	+	+	
^b 142R-2, 73-75	1355.0	+	+		+	+		+			+	+		
142R-2, 73-75	1355.0	+	+		+	+		+			+	+		
143R-1, 33-35	1359.6	+	+	+	+		+							
^b 143R-1, 108–112	1360.4	+	+	+	+	+		+				+		
144R-1, 0-2	1368.7	+	+		+	+		+					+	
^b 144R-1, 43-47	1369.1	+	+	+	+	+		+						
144R-1, 86-88	1369.6	+	+	+	+			+						
144R-1, 110-111	1369.8	+	+		+			+						
^b 145R-3, 137-138	1384.2	+	+		+	+		+				+	+	
145R-4, 20-22	1384.5	+	+		+			+			+	+	+	
146R-1, 7-9	1388.1	+	+		+	+		+			+		+	
147R-2, 30-33	1399.2	+	+		+	+		+		+			+	
149R-2, 12-15	1418.5	+	+		+			+						
^b 149R-2, 50-53	1418.9	+	+		+	+		+	+	+	+	+	+	
^b 149R-2, 57-59	1419.0	+	+		+	+		+		+	+		+	
150R-1, 54-56	1426.9	+	+		+			+			+			
150R-1, 54-56	1426.9	+	+		+	+		+					+	
^b 150R-1, 81-83	1427.2	+	+		+	+		+					+	
151R-1, 33-35	1431.1	+	+		+	+		+	+		+		+	
^b 152R-1, 5-8	1436.0	+	+			+		+	+		+		+	
^b 152R-1, 17-19	1436.1		+			+		+	+	+	+		+	Ah
^b 152R-1, 61-64	1436.5	+	+		+	+		+	+	+	+			Ah/Mp
152R-1, 81-84	1436.7	+	+		+	+		+					+	
152R-1, 120-122	1437.1	+	+		+			+			+		+	
^b 153R-1, 77-79	1446.1	+	+		+	+		+			+		+	Mp
^b 154R-1, 116-119	1455.5	+	+		+	+		+				+	+	
^b 156R-1, 37-39	1464.2	+	+			+		+	+		+			
^b 157R-1, 1-6	1473.1	+	+		+	+		+			+		+	
^b 157R-1, 2-5	1473.1	+	+		+	+		+					+	
157R-1, 8-12	1473.2	+	+		+	+		+		+	+		+	
⁰ 157R-1, 60-63	1473.7	+	+		+	+		+	+		+		+	
⁰ 158R-1, 16-18	1482.7	+	+		+	+		+	+		+	+	+	
^b 158R-1, 18-20	1482.7		+			+		+			+	+	+	
⁰ 158R-1, 32-34	1482.8		+			+	+	+	+	+	+	+	+	
⁰ 158R-1, 30-34	1482.8		+			+	+	+	+	+	+	+	+	
^b 159R-1, 27-29	1488.4	+	+		+	+		+					+	
^b 159R-1, 52-56	1488.6	+	+		+	+		+			+		+	
^b 160R-1, 25-27	1495.0	+	+		+	+		+				+	+	
⁶ 160R-1, 59-60	1495.3	+	+		+	+		+				+	+	
163R-1, 37-39	1512.0	+	+		+	+		+		+	+			
163R-1, 135-138	1513.0		+		+	+		+		+				
164R-1, 55-58	1515.7	+	+		+	+		+			+		+	
165R-1, 72-76	1530.2	+	+		+	+		+					+	
166R-1, 8-12	1543.6	+	+		+	+		+			+			
169R-1, 28-31	1547.9	+	+	+	+	+		+				+		
0170R-1, 49-53	1554.1	+	+		+	+		+	+				+	

Note: All include small amounts of clay, talc, sulfide, and Fe-Ti oxide. a Ah = anhydrite; Mp = metamorphic clinopyroxene. b Analyzed samples.



Figure 1. Photomicrographs showing replacement textures of primary (igneous) phases by secondary minerals. The scale bar is 0.5 mm in length. **A.** Totally altered olivine phenocryst to talc (Tc), quartz (Qz), and aggregate (Agg) of actinolite and chlorite. A tiny and euhedral crystal of relict Cr spinel (RS) is at the center of the olivine pseudomorph. Sample 111-504B-168R-1, 28-31 cm (plane polarized light). **B.** Partially altered clinopyroxene phenocryst to actinolite (At) and chlorite (Chl). Sample 111-504B-157R-1, 1-6 cm (plane polarized light). **C.** Totally altered plagioclase phenocryst to prehnite (Pr) and stilbite (St). Sample 111-504B-142R-1, 118-121 cm (crossed nichols). **D.** Partially altered plagioclase phenocryst to anhydrite (Anh). Sample 111-504B-152R-1, 17-19 cm (crossed nichols).

chlorites in a single thin section show a rather restricted composition. The compositions of chlorites on the diagram of Hey (1954) plot as dominantly pycnochlorite and less commonly penninite, diabantite, ripidolite, and brunsvigite.

Epidote

Epidote (Table 6) occurs sporadically only in veins, forming spongy or acicular crystal aggregates. No epidote was found replacing primary minerals such as plagioclase.

The frequency distribution of $XFe = Fe^{3+}/(Fe^{3+} + Al)$ of epidote is illustrated in Figure 5. In these samples, the epidotes are relatively homogeneous in relation to the XFe content. Furthermore, the XFe content is apparently higher in epidote associated with laumontite + prehnite than in that with actinolite + prehnite. The MnO content is negligible, up to 0.10 wt%. The MgO content of some epidotes in Sample 111-504B-158R-1, 30-34 cm, is, however, remarkably high (1.91–1.98 wt%); such MgO-rich epidote is tentatively termed "magnesian epidote" by Cho and Liou (1987).

Metamorphic Plagioclase

Metamorphic plagioclase (Table 7) occurs as discrete patches after plagioclase phenocrysts and groundmass and as fine-grained aggregates in veins and in breccia matrix. Some metamorphic plagioclase replacing primary plagioclase displays a cloudy appearance.

The variations of the An content = 100Ca/(Ca + Na)against the Fe₂O₃* and MgO contents of metamorphic plagioclase are shown in Figure 6, which also includes the compositions of primary plagioclases plotted for comparison. The metamorphic plagioclases are mainly albitic in composition, but there are several plagioclases with oligoclase compositions. Most importantly, the coexistence of albite and oligoclase is found as discrete patches replacing primary plagioclases in Samples 111-504B-142R-1, 118-121 cm, 111-504B-149R-2, 50-53 cm, and 111-504B-157R-1, 1-6 cm, and as fine-grained aggregates in veins in Sample 111-504B-158R-1, 30-34 cm. This may indicate that the "peristerite gap" may occur in Hole 504B. Compared with the compositions of the primary plagioclase, all analyzed metamorphic plagioclases have the lower An content, and also they are poorer in MgO (less than 0.06 wt%) and Fe₂O_{3*} (less than 0.32 wt%). The K₂O content is very low both in metamorphic (less than 0.06 wt%) and primary (less than 0.08 wt%) plagioclase.

Amphibole

Amphibole minerals (Table 8) occur ubiquitously throughout the examined rocks. Most commonly, they are found as acicular to prismatic crystals scattered in pseudomorphs after olivine.



Figure 2. Photomicrographs of veins (all in plane polarized light). The scale bar is 0.2 mm in length except as noted. A. Prehnite-epidote-laumontite (Pr-Ep-Lm) vein. Sample 111-504B-142R-1, 118-121 cm. B. Prehnite-actinolite-epidote (Pr-At-Ep) vein. Sample 111-504B-158R-1, 32-34 cm. C. Prehnite (white)-actinolite (acicular crystal)-chlorite (gray) vein. Sample 111-504B-152R-1, 5-8 cm. D. Acicular to prismatic sodic augite in chlorite vein. A persisting tabular primary clinopyroxene (Cx) is also slightly altered to chlorite and sodic augite around the margin. Sample 111-504B-152R-1, 61-64 cm. Scale bar is 0.1 mm in length.

As a partial replacement of primary clinopyroxene they are restricted to the margin around and cracks within clinopyroxene; they take the form of acicular crystals along the margin and fibrous crystal aggregates along the cracks. In veins, fractures, vugs, or breccia matrix acicular to prismatic amphiboles are common, up to 1.0 mm in length.

The analyzed amphiboles, for which the atomic proportions were calculated on the basis of 23 oxygens, can be divided first into orthorhombic and monoclinic amphiboles.

The orthorhombic amphiboles, which occur only in olivine pseudomorphs in Sample 111-504B-169R-1, 28–31 cm, are mainly composed of SiO₂, FeO*, and MgO. The Si and Mg/(Mg + Fe) values range from 7.92 to 7.95 and from 0.79 to 0.84, respectively, indicating that these orthorhombic amphiboles can be classified as anthophyllite in the sense of Leake (1978). Besides these major oxides, the anthophyllites contain small amounts of Al₂O₃ (up to 0.78 wt%), MnO (up to 0.10 wt%), CaO (up to 0.28 wt%), and Na₂O (up to 0.08 wt%).

On the basis of the (Ca + Na)B value of Leake (1978), the monoclinic amphiboles are further divided into Fe-Mg amphiboles—(Ca + Na)B < 0.5—and Ca amphiboles—(Ca + Na)B > 0.8 (Fig. 7). In the sense of Leake (1978), the term Ca amphibole is used where the (Ca + Na)B value is more than 1.34.

However, this value of the Leg 111 Ca amphiboles ranges continuously from 2.0 to 0.8, and, hence, in this work amphiboles with a (Ca + Na)B value more than 0.8 are termed Ca amphibole. There is no amphibole with a (Ca + Na)B value intermediate between 0.5 and 0.8.

The Fe-Mg amphiboles have Mg/(Mg + Fe) values of 0.63 to 0.80 and are classified as magnesiocummingtonite to cummingtonite in the sense of Leake (1978). Besides the major oxides of SiO₂, FeO, and MgO, some Fe-Mg amphiboles contain appreciable amounts of Al₂O₃ (up to 7.33 wt%). These Al-rich Fe-Mg amphiboles are also rich in TiO₂ (up to 0.30 wt%) and Na₂O (up to 0.53 wt%).

From a plot of compositions on the diagram of Leake (1978) (Fig. 8), the Ca amphiboles with a (Ca + Na)B value more than 1.34 range dominantly from actinolite or ferroactinolite, through ferroactinolitic hornblende or actinolitic hornblende, to magnesiohornblende; some are scattered in the fields of ferrohornblende, tschermakitic hornblende, ferrotschermakitic hornblende, and tschermakite. The Al-rich calcic amphiboles generally tend to contain appreciable amounts of TiO₂ and Na₂O. On the other hand, the Ca amphiboles with a (Ca + Na)B value less than 1.34, which are not plotted in Figure 8, have both actinolitic (Si > 7.25) and hornblendic (Si < 7.25) compositions

rable 2. Composition of selected secondary minerals, Hole 504B, ODP Leg 11	Table 2.	Composition	of selected	secondary	minerals,	Hole	504B,	ODP	Leg 1	111.
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Core, section, interval (cm)	Depth (mbsf)	Amphibole ^a	Epidote ^b (XFe)	Chlorite ^c (XFe)	Prehnite ^b (XFe)	Zeolite ^d	Metamorphic plagioclase ^e (An-Cont)	Quartz	Sphene ^f (XTi)
142R-1, 2-4	1352.8	At/Hb		35-36					89-90
142R-1, 118-121	1354.0	At/Hb	25-27	37-42	19-13	Lau/Sti	4/28	+	90-91
142R-2, 73-75	1355.0	At		39-42			14	+	
143R-1, 108-112	1360.4	Cm/At		32-39				+	
144R-1, 43-47	1369.1	Cm/At/Hb		30-34					
145R-3, 137-138	1384.2	Cm/At/Hb						+	
147R-2, 30-33	1399.2	At		39-58		Lau			71-72
149R-2, 50-53	1418.9	At		40-44	10-11	Sti	3/19	+	
149R-2, 57-59	1419.0	At		38-39		Lau			
150R-1, 81-83	1427.2	At		39-40					
152R-1, 5-8	1436.0	At/Hb		43-44	10-11		3		
152R-1, 17-19	1436.1	At/Hb		41-45	2-3	Lau/Sti	6/7		
152R-1, 61-64	1436.5	At		40-41			3/4		
153R-1, 77-79	1446.1	At		41-51			2/3		79-82
154R-1, 116-119	1455.5	At		42-45				+	85-92
156R-1, 37-39	1464.2	At/Hb		42-43	5-13		11		
157R-1, 1-6	1473.1	At		37-46			4/11/19		
157R-1, 2-5	1473.1	At		40-41					
157R-1, 60-63	1473.7	At		40-41	6-14		2/3/4/5		
158R-1, 16-18	1482.7	At		40-41			9	+	
158R-1, 18-20	1482.7	At		40-42			11/13	+	86-87
158R-1, 32-34	1482.8	At	19-21	45-46	9-10	Lau		+	
158R-1, 30-34	1482.8	At	16-21	42-44	7-8	Lau/Sti	3/4/4/4/20	+	88-93
159R-1, 27-29	1488.4	At		40-45					
159R-1, 52-56	1488.6	At/Hb		46-51				+	85-88
160R-1, 25-27	1495.0	At		39-40				+	82-88
160R-1, 59-60	1495.3	At		37-46				+	86-88
163R-1, 135-138	1513.0	Hb		42-51		Lau/Sti			
164R-1, 55-58	1515.7	At/Hb		37-42			8		
165R-1, 72-76	1530.2	At		39-40					
169R-1, 28-31	1547.9	Ap/Cm/ At/Hb		39-41				+	
170R-1, 49-53	1554.1	At/Hb		41-47	4-5				84-90

Note: All include small amounts of clay, talc, sulfide, and Fe-Ti oxide.

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 e^{e} An-Cont = 100Ca/(Ca + Na), f XTi = 100Ti/(Ti + Al + Fe²⁺).

Table 3. Represe	ntative zeolite	analyses,	Hole	504B,	ODP	Leg	111.
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Species	Core, section, interval (cm)	Depth (mbsf)	SiO_2	Al ₂ O ₃	Fe ₂ O ₃ ^a	CaO	Na ₂ O	K ₂ O	Total
Laumontite	142R-1, 118-121	1354.0	52.18	22.27	0.13	12.01	0.13	0.01	86.73
			53.98	20.70	0.26	11.28	0.51	0.07	86.80
	147R-2, 30-33	1399.2	54.46	20.88	0.00	11.07	0.37	0.04	86.82
	149R-2, 57-59	1419.0	53.51	20.98	0.00	10.98	0.58	0.00	86.05
			53.71	20.94	0.00	11.18	0.66	0.00	86.49
	158R-1, 30-34	1482.8	54.37	21.97	0.22	11.16	0.22	0.00	87.94
			53.88	21.74	0.10	11.50	0.20	0.04	87.46
	163R-1, 135-138	1513.0	55.22	21.38	0.02	10.94	0.44	0.08	88.08
			54.22	20.88	0.07	10.65	0.39	0.08	86.29
Stilbite	142R-1, 118-121	1354.0	57.90	16.18	0.07	8.70	0.23	0.02	83.10
			58.83	16.95	0.00	9.25	0.28	0.00	85.31
	149R-2, 50-53	1418.9	59.85	16.69	0.50	8.90	0.18	0.04	86.16
	152R-1, 17-19	1436.1	59.53	15.98	0.07	8.31	0.18	0.02	84.09
			59.75	16.49	0.02	8.88	0.21	0.05	85.40
	152R-1, 61-64	1436.5	59.31	14.74	0.04	8.49	0.21	0.02	82.81
	158R-1, 30-34	1482.8	58.23	17.82	0.10	9.45	0.14	0.05	85.79
	EN SELEVARIAS DE PERSON		57.30	18.62	0.05	9.46	0.24	0.04	85.71
	163R-1, 135-138	1513.0	56.75	17.36	0.17	8.99	0.29	0.02	83.58
	1897년(1997년) 2월 4일 전 전 1997년 (1997년) 1997년 - 1997년 (1997년) 1997년 (1997년) 1997년 - 1997년 (1997년) 1997년 (1997년) 1997년)		57.21	18.51	0.03	9.60	0.21	0.01	85.57

^a Total iron as Fe₂O₃.

with the Mg/(Mg + Fe) ratio ranging from 0.33 to 0.69 and from 0.53 to 0.64, respectively. Such amphiboles have been rarely reported in the literature (e.g., Robinson et al., 1982).

For these Ca amphiboles, especially for the actinolitic Ca amphiboles, considerable variations are typically found in (Fe

+ Mg) and Ca (Fig. 9), and there is a negative correlation between (Fe + Mg) and Ca. This may indicate that significant substitution of Ca for (Fe + Mg) occurs.

The following pairs of amphibole species were occasionally observed as coexisting as discrete crystals in a single vein or vug

Table 4. Representative prehnite analyses, Hole 504B, ODP Leg 111.

Corre continu	Dent										Fe ³⁺
interval (cm)	(mbsf)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^a	MnO	MgO	CaO	Na ₂ O	Total	$(Fe^{3+} + Al)$
142R-1, 118-121	1354.0	43.71	0.00	19.85	7.30	0.00	0.05	25.26	0.03	96.20	0.19
		43.77	0.01	21.45	5.07	0.03	0.02	26.62	0.09	97.06	0.13
149R-2, 50-53	1418.9	43.72	0.00	22.16	4.18	0.00	0.31	25.58	0.09	96.04	0.11
152R-1, 5-8	1436.0	42.56	0.00	21.47	4.21	0.00	0.00	26.00	0.00	94.24	0.11
152R-1, 17-19	1436.1	43.53	0.02	25.01	0.97	0.00	0.03	26.57	0.00	96.13	0.02
156R-1, 37-39	1464.2	43.69	0.00	21.60	5.04	0.00	0.03	26.18	0.07	96.61	0.13
		43.64	0.09	23.32	3.03	0.00	0.04	26.25	0.03	96.40	0.08
157R-1, 60-63	1473.2	43.50	0.00	21.53	5.02	0.00	0.01	26.26	0.08	96.40	0.13
		44.14	0.02	23.62	2.36	0.07	0.01	26.23	0.03	96.48	0.06
158R-1, 32-34	1482.8	44.29	0.00	22.38	3.27	0.00	0.00	25.81	0.04	95.79	0.08
158R-1, 30-34	1482.8	43.94	0.00	22.38	2.96	0.00	0.02	25.71	0.09	95.10	0.08
		44.08	0.03	22.74	2.71	0.00	0.00	25.87	0.04	95.47	0.07
170R-1, 49-53	1554.1	43.29	0.00	23.87	1.76	0.02	0.25	26.25	0.00	95.44	0.04

^a Total iron as Fe₂O₃.



Figure 3. Frequency distribution of the $Fe^{3+}/(Fe^{3+} + AI)$ ratio for prehnite. Dots and stars represent analyses of prehnites coexisting with epidote and laumontite and with epidote and actinolite, respectively.

or olivine pseudomorph: actinolite + hornblende (Samples 111-504B-142R-1, 2-4 cm, and 111-504B-142R-1, 118-121 cm, 111-504B-159R-1, 52-56 cm, and 111-504B-170R-1, 49-53 cm), actinolite-cummingtonite (Samples 111-504B-144R-1, 43-47 cm, and 111-504B-169R-1, 28-31 cm), hornblende + cummingtonite (Sample 111-504B-145R-3, 137-138 cm), and hornblende + cummingtonite + anthophyllite (Sample 111-504B-169R-1, 28-31 cm). This may reflect the compositional gap between each amphibole pair (Robinson et al., 1982).

A preliminary analysis of chlorine using EDS indicates that the amphiboles are enriched in Cl content, up to 0.2 wt%, and further, that in the same thin section, the Cl content is higher in amphiboles filling veins than in those replacing clinopyroxene. This may suggest the presence of a saline hydrothermal fluid or a fluid of near seawater salinity (Vanko, 1986).

Other Secondary Minerals

Other secondary minerals analyzed here include sodic augite, sphene, talc, anhydrite, chalcopyrite, pyrite, and Fe-Ti oxide (Table 9); sulfur of anhydrite, chalcopyrite, and pyrite were not analyzed.

Sodic Augite

Sodic augite is found only in veins from Samples 111-504B-152R-1, 61-64 cm, and 111-504B-153R-1, 77-79 cm, taking the form of acicular crystal aggregates. Compared with the primary clinopyroxene in the same thin section, the sodic augite is higher in Al₂O₃, CaO, and Na₂O and lower in TiO₂ and MgO. One of the analyzed sodic augites is, however, rich in the TiO₂ content (2.47 wt%). Laverne (1983) described aegirine-augite from 298 m below the top of basement recovered from Hole 504B during DSDP Leg 70. Compared with the aegirine-augite compositions of Leg 70, the sodic augite recovered during Leg 111 is richer in Al₂O₃ and poorer in FeO* and Na₂O.

Sphene

Sphene occurs commonly as dusty aggregates intimately associated with opaque phases and as individual anhedral grains of less than 0.5 mm diameter scattered in veins, vugs, and breccia matrix. The analyses of sphene exhibit relatively constant proportions of SiO₂ (29.8–31.2 wt%) and CaO (27.0–28.0 wt%), but show some variations of TiO₂ (29.2–37.7 wt%), Al₂O₃ (1.3– 6.4 wt%), and FeO* (0.7–2.5 wt%). All other analyzed elements (Cr₂O₃, MnO, MgO, Na₂O, and K₂O) occur in insignificant amounts.

Talc

Talc, which is generally restricted to platy crystal aggregates in pseudomorphs after olivine, is mainly composed of SiO₂ and MgO, but also contains appreciable amounts of Al₂O₃ and FeO*, up to 4.2 and 9.7 wt%, respectively. Of these elements, the Al₂O₃ and FeO* contents vary antithetically to the SiO₂ and MgO contents, respectively. This suggests Al-Si and Fe-Mg substitutions.

Anhydrite

Anhydrite, found in Samples 111-504B-152R-1, 17-19 cm, and 111-504B-152R-1, 61-64 cm, as discrete patches after plagioclase phenocrysts, contains a CaO content of 37.8-39.7 wt% with little or no amounts of other oxides present.

Chalcopyrite and Pyrite

Chalcopyrite and pyrite, commonly replacing primary magnetite and rarely rimming olivine pseudomorphs, have FeO* contents of 39.7-44.3 and 59.0-60.9 wt%, respectively. Other oxides in these sulfide minerals occur in insignificant amounts, but some of the Na₂O content is enriched, up to 0.54 wt% in chalcopyrite and 0.36 wt% in pyrite.

Table 5. Representative chlorite analyses, Hole	504B,	ODP	Leg	111.
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Core, section,	Depth								Fe ²⁺	
interval (cm)	(mbsf)	SiO ₂	Al_2O_3	FeO*a	MnO	MgO	CaO	Total	$(\mathrm{Fe}^{2+} + \mathrm{Mg})$	Species ^b
142R-1, 2-4	1352.8	29.67	19.12	19.49	0.12	19.34	0.12	87.86	0.36	Pycno.
142R-1, 118-121	1354.0	28.10	19.46	21.23	0.20	17.72	0.14	86.85	0.40	Pycno.
142R-2, 73-75	1355.0	29.65	17.35	22.49	0.11	17.31	0.31	87.22	0.42	Pycno.
		29.74	15.41	22.17	0.10	18.03	0.19	85.64	0.41	Diaba.
143R-1, 108-112	1360.4	26.66	15.53	20.53	0.19	21.26	0.23	84.40	0.35	Pycno.
144R-1, 43-47	1369.1	31.94	14.71	17.23	0.11	23.04	0.24	87.27	0.30	Diaba.
147R-2, 30-33	1399.2	28.33	15.09	28.07	0.20	14.69	0.16	86.54	0.52	Bruns.
		29.29	17.52	21.91	0.25	19.60	0.17	88.74	0.39	Pycno.
149R-2, 50-53	1418.9	27.77	18.31	24.03	0.17	16.85	0.02	87.15	0.44	Pycno.
149R-2, 57-59	1419.0	26.50	17.90	20.08	0.00	18.21	0.18	82.87	0.38	Pycno.
150R-1, 81-83	1427.2	27.30	17.70	20.95	0.00	18.40	0.25	84.60	0.39	Pycno.
152R-1, 5-8	1436.0	26.68	18.52	22.40	0.21	16.88	0.00	84.69	0.43	Pycno.
152R-1, 17-19		28.42	17.37	23.72	0.18	17.55	0.08	87.32	0.43	Pycno.
152R-1, 61-64	1436.5	31.19	16.59	21.89	0.16	18.97	0.44	89.24	0.39	Diaba.
153R-1, 77-79	1446.1	27.39	18.77	22.60	0.18	17.53	0.07	86.54	0.42	Pycno.
		26.80	19.54	26.39	0.31	13.87	0.24	87.15	0.52	Bruns.
154R-1, 116-119	1455.5	26.96	18.75	23.29	0.19	17.54	0.09	86.82	0.43	Pycno.
156R-1, 37-39	1464.2	27.93	19.30	23.05	0.19	17.63	0.21	88.31	0.42	Pycno.
157R-1, 1-6	1473.1	27.47	18.92	22.01	0.19	17.59	0.08	86.26	0.41	Pycno.
		26.81	19.19	21.69	0.23	18.58	0.06	86.56	0.40	Ripid.
157R-1, 2-5	1473.1	27.50	16.93	20.91	0.00	17.86	0.21	83.41	0.40	Pycno.
157R-1, 60-63	1473.7	27.14	17.84	21.03	0.15	17.94	0.31	84.41	0.40	Pycno.
158R-1, 16-18	1482.7	27.86	17.37	21.56	0.00	18.08	0.33	85.20	0.40	Pycno.
158R-1, 18-20	1482.7	27.96	18.18	23.45	0.07	18.20	0.13	87.99	0.42	Pycno.
158R-1, 32-34	1482.8	26.88	17.98	23.64	0.00	16.18	0.26	84.94	0.45	Pycno.
158R-1, 30-34	1482.8	27.79	19.77	23.53	0.26	17.08	0.27	88.70	0.44	Pycno.
		26.79	19.67	24.21	0.23	17.05	0.18	88.13	0.44	Ripid.
159R-1, 27-29	1488.4	27.69	18.74	23.76	0.13	16.30	0.15	86.77	0.45	Pycno.
159R-1, 52-56	1488.6	27.11	16.41	27.77	0.16	14.73	0.10	86.28	0.51	Bruns.
		26.61	17.88	24.68	0.19	16.28	0.06	85.70	0.46	Pycno.
160R-1, 25-27	1495.0	27.21	19.59	21.13	0.25	18.78	0.09	87.05	0.39	Pycno.
160R-1, 59-60	1495.3	27.02	19.17	20.88	0.15	18.78	0.09	86.09	0.38	Pycno.
163R-1, 135-138	1513.0	27.08	18.22	27.32	0.15	14.92	0.15	87.84	0.51	Bruns.
		27.92	18.18	23.44	0.18	17.19	0.13	87.04	0.43	Pycno.
164R-1, 55-58	1515.7	27.77	20.24	20.29	0.13	19.17	0.11	87.71	0.37	Pycno.
165R-1, 72-76	1530.2	28.11	18.61	21.15	0.12	17.94	0.16	86.09	0.40	Pycno.
169R-1, 28-31	1547.9	27.41	16.63	21.57	0.27	19.11	0.15	85.14	0.39	Pycno.
		28.70	16.64	20.42	0.10	16.52	0.36	82.74	0.41	Diaba.
170R-1, 49-53	1554.1	26.64	18.79	23.63	0.14	16.92	0.05	86.17	0.44	Pycno.

^a Total iron as FeO.

^b Pycno. = pycnochlorite; Diaba. = diabantite; Bruns. = brunsvigite; Ripid. = ripidolite.

Fe-Ti Oxide

Fe-Ti oxide, mainly occurring as partial or total replacement of primary opaque phases such as Cr spinel and magnetite, exhibits wide variations in major oxides; the TiO₂ contents range from 28.4 to 11.2 wt%, and the FeO* contents range from 53.6 to 77.0 wt%.

MINERAL PARAGENESIS

The mineral assemblages observed in the altered basalts from Hole 504B can be generally represented by the model chemical system SiO2-TiO2-Al2O3-Fe2O3-FeO-MgO-CaO-Na2O-H2O, assuming that MnO (up to 0.20 wt%) and K2O (up to 0.05 wt%) are minor components (shipboard X-ray-fluorescence analyses; Shipboard Scientific Party, 1988). SiO2, TiO2, and Na2O are assumed to be fixed in quartz, sphene, and sodic plagioclase, respectively. If the fluid phase is assumed to be in excess and consisting mainly of H₂O, H₂O can be considered a perfectly mobile component. Furthermore, if the chlorite composition is fixed at constant Fe/(Fe + Mg), the system can be simplified to the four components Al₂O₃-Fe₂O₃-(Fe/Mg)O-CaO (Fig. 10A). In order to graphically evaluate the mineral paragenesis and the effect of Al-Fe³⁺ substitution in Ca-Al silicates (epidote and prehnite), the chlorite projection onto the Al₂O₃(A)-Fe₂O₃(F)-CaO(C) plane as described by Liou et al. (1985a) is adopted in this study (Fig. 10B), mainly because chlorite is ubiquitous in the samples.

The mineral associations and chemistries in the samples examined here generally show some variations from place to place in each thin section. Such variations, which can be attributed to local differences in effective bulk compositions, make it difficult to define the equilibrium compositions and compatibilities of the coexisting minerals in very low-grade metamorphic rocks (e.g., Liou et al., 1987). In this case, minerals in contact are generally assumed to represent equilibrium, as suggested by Zen (1974). In fact, it is extremely difficult to find two or three Ca-Al silicates together with chlorite, albite and/or oligoclase, quartz, and sphene in a contact relationship in an assumed equilibrium domain. For the practical purposes of the present study, therefore, the analyzed compositions for a group of minerals within veins or fractures 1-10 mm in thickness or one vug a few millimeters in diameter or for minerals replacing relict phases in a single thin section are considered together to approximate the equilibrium compositions. However, the mineral associations in veins that show texturally multistage mineral formation are omitted.

On the basis of the procedure for the definition of the mineral assemblages described in the preceding, the secondary mineral assemblages observed in the altered basalts recovered from Hole 504B during ODP Leg 111 can be classified into the following seven types in terms of the model basaltic system: (1) amphibole, (2) prehnite + zeolite, (3) prehnite + amphibole, (4) amphibole + zeolite, (5) prehnite + amphibole + zeolite, (6) epidote + prehnite + zeolite, and (7) amphibole + prehnite



Figure 4. Compositional variation of Al-Fe-Mg for chlorite.

Table 6. Representative epidote analyses, Hole 504B, ODP Leg 111.

Core, section, interval (cm)	Depth (mbsf)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ * ^a	MnO	MgO	CaO	Total	$\frac{\mathrm{Fe}^{3+}}{(\mathrm{Fe}^{3+} + \mathrm{Al})}$
142R-1, 118-121	1354.0	38.12	22.72	12.23	0.07	0.08	23.57	96.79	0.26
		37.91	22.79	13.12	0.08	0.06	23.50	97.46	0.27
158R-1, 32-34	1482.8	38.22	26.22	9.35	0.10	0.03	23.77	97.69	0.19
158R-1, 30-34	1482.8	38.40	26.99	8.20	0.08	0.03	23.89	97.59	0.16
2		37.27	23.71	9.74	0.02	1.96	22.12	94.82	0.21
		36.60	23.29	8.56	0.08	1.96	22.04	92.53	0.19

^a Total iron as Fe₂O₃.



Figure 5. Frequency distribution of the $Fe^{3+}/(Fe^{3+} + AI)$ ratio for epidotes. Dots and stars represent analyses of epidotes coexisting with prehnite and laumontite and with prehnite and actinolite, respectively.

+ epidote, all including chlorite, albite and/or oligoclase, quartz, and sphene. Of these, the amphibole-zeolite association may represent a disequilibrium assemblage as described previously. Thus, the low-variance (three-phase) mineral assemblages such as types (6) and (7), which were rarely observed in the examined rocks (Table 1), must be important for consideration of mineral paragenesis. Compositionally, the amphibole and zeolite in these two types of the mineral assemblages are actinolite and laumontite, respectively. The mineral parageneses of types (6) and (7) assemblages are depicted in the AFC projections of Figures 10C and 10D, respectively. Besides the presence or absence of laumontite and actinolite, consideration of the $Al-Fe^{3+}$ substitution of prehnite and epidote finds that the epidote-prehnite tie-line shifts toward the Al-Ca line from type (6) to type (7) assemblages.

The mineral paragenesis of Figure 10C is characterized by the mineral assemblage laumontite-prehnite-epidote (+ chlorite, + albite and/or oligoclase, + quartz, + sphene). This is one of the diagnostic mineral assemblages of the zeolite facies (e.g., Cho et al., 1986; Liou et al., 1987), described in the Onikobe geothermal system of northeast Japan (Liou et al., 1985b). This low-variance mineral assemblage indicates that the reaction laumontite + prehnite = epidote + quartz + fluid does not occur perfectly; this reaction generally defines the upper stability of the zeolite facies (Cho et al., 1986). It is, therefore, most likely that the mineral paragenesis of Figure 10C represents the higher grade part of the zeolite facies. The mineral assemblage of type (2) may represent a partial mineral assemblage of the higher grade part of the zeolite facies.

Core section	Depth									100 Ca
interval (cm)	(mbsf)	SiO ₂	Al_2O_3	Fe ₂ O ₃ ^a	MgO	CaO	Na ₂ O	K ₂ O	Total	(Ca + Na)
142R-1, 118-121	1354.0	64.63	23.51	0.02	0.00	5.02	7.09	0.00	100.27	28.12
		67.10	21.38	0.04	0.00	0.90	11.46	0.03	100.91	4.16
142R-2, 73-75	1355.0	64.09	22.27	0.30	0.05	2.74	9.64	0.02	99.11	13.57
149R-2, 50-53	1418.9	66.70	20.87	0.16	0.01	0.68	11.73	0.05	100.20	3.10
		63.00	23.75	0.23	0.03	4.07	9.52	0.01	99.61	19.11
152R-1, 5-8	1436.0	66.44	19.17	0.31	0.00	0.62	11.47	0.00	98.01	2.90
152R-1, 17-19	1436.1	66.52	20.87	0.17	0.00	1.36	10.44	0.02	99.38	6.72
		67.13	21.35	0.01	0.02	1.28	10.95	0.02	100.76	6.07
152R-1, 61-64	1436.5	67.16	21.01	0.16	0.01	0.86	11.52	0.05	100.77	3.96
		67.18	20.59	0.06	0.00	0.64	11.41	0.01	99.89	3.01
153R-1, 77-79	1446.1	66.82	21.27	0.05	0.03	0.74	11.47	0.02	100.40	3.44
		67.20	20.36	0.24	0.00	0.53	11.72	0.00	100.05	2.44
156R-1, 37-39	1464.2	66.20	21.37	0.07	0.06	2.12	9.79	0.02	99.63	10.69
157R-1, 1-6	1473.1	62.80	23.76	0.18	0.03	3.81	8.96	0.05	99.59	19.03
-5-16-6-12-26-5-8-6-6-7-5		66.58	21.49	0.07	0.01	0.90	11.14	0.01	100.20	4.27
		64.27	22.74	0.12	0.06	2.27	10.53	0.03	100.02	10.64
157R-1, 60-63	1473.7	67.22	20.90	0.20	0.05	0.83	11.43	0.00	100.63	3.86
		68.97	20.15	0.10	0.00	0.46	11.02	0.00	100.70	2.25
		67.71	20.64	0.02	0.00	0.57	11.56	0.06	100.56	2.65
		66.43	20.22	0.32	0.03	1.18	10.80	0.03	99.01	5.69
158R-1, 16-18	1482.7	65.46	20.80	0.21	0.00	1.83	10.80	0.00	99.10	8.56
158R-1, 18-20	1482.7	65.44	22.65	0.11	0.00	2.38	10.40	0.00	100.98	11.23
POINTER AN EXCITES		64.12	23.45	0.27	0.02	2.82	10.18	0.00	100.86	13.28
158R-1, 30-34	1482.8	62.16	24.04	0.10	0.01	4.29	9.66	0.05	100.31	19.71
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	11053634	66.93	21.15	0.00	0.01	0.86	11.05	0.01	100.01	4.12
		68.35	19.83	0.30	0.03	0.64	11.35	0.02	100.52	3.02
164R-1, 55-58	1515.7	65.88	22.10	0.00	0.03	1.71	10.76	0.02	100.50	8.07

Table 7. Representative metamorphic plagioclase analyses, Hole 504B, ODP Leg 111.

^a Total iron as Fe₂O₃.



Figure 6. Variations of MgO and  $Fe_2O_3^*$  contents against An content for primary (igneous) and metamorphic plagioclases. The tie-lines represent a coexisting albite and oligoclase pair.

Table 8.	. Representative	amphibole analyses,	Hole 504B.	, ODP	Leg	111.
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Core, section, interval (cm)	Depth (mbsf)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO ^a	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cl	Total
Anthophyllite												
169R-1, 28-31	1547.9	57.48	0.00	0.30	9.67	0.10	28.40	0.28	0.02	0.00	nd	96.25
Cummingtonite												
143R-1, 108-112	1360.4	47.84	0.30	7.33	18.35	0.26	19.85	1.03	0.53	0.01	nd	95.50
144R-1, 43-47	1369.1	56.52	0.00	1.32	14.16	0.12	24.69	0.38	0.11	0.00	nd	97.30
145R-3, 137-138	1384.2	56.08	0.05	1.94	11.57	0.10	26.52	1.16	0.17	0.00	nd	97.59
169R-1, 28-31	1547.9	55.78	0.00	0.78	15.06	0.16	24.02	0.51	0.13	0.00	nd	96.44
Actinolitic Ca-amphib	ole with S	i > 7.25	and (Ca	+ Na)B	> 1.34							
142R-1, 2-4	1352.8	53.07	0.52	2.89	14.18	0.23	15.40	10.30	0.37	0.10	nd	97.06
		49.93	0.21	4.35	16.75	0.38	15.56	8.19	0.32	0.03	nd	95.72
142R-1, 118–121	1354.0	50.88	0.26	3.77	18.75	0.34	11.74	10.93	0.37	0.01	nd	97.05
142R-2, 73-75	1355.0	51.45	0.24	3.90	19.18	0.23	10.91	11.60	0.34	0.00	nd	97.85
1430 1 100 113	12/0 4	48.18	0.06	5.70	19.31	0.50	12.77	8.11	0.41	0.00	nd	95.04
143K-1, 108-112	1360.4	50.65	0.06	5.35	14.76	0.29	14.30	8.68	0.49	0.05	nd	94.09
144K-1, 43-47	1369.1	50.51	0.05	4.49	15.80	0.37	14.43	10.06	0.49	0.02	nd	96.22
145K-3, 137-138	1384.2	52.69	0.27	2.70	14.60	0.24	15.58	11.46	0.41	0.04	nd	97.99
14/18-2, 50-55	1399.2	50.54	0.08	2.00	18.34	0.30	0.16	7 21	0.22	0.00	nd	90.72
140P.2 50.53	1418 0	52.04	0.44	2.37	14.76	0.01	14.97	12 51	0.00	0.08	nd	90.99
1471-2, 50-55	1410.9	53.85	0.39	1.27	17 26	0.20	15 57	9.91	0.40	0.02	nd	08 14
149R-2 57-59	1419.0	49 69	0.35	4 18	18.26	0.39	12.52	9.94	1 18	0.02	0.17	96.36
14710-2, 57-55	1417.0	48 58	0.35	4.10	21 25	0.32	9.63	9.80	1.09	0.00	0.20	95 23
		52.53	0.33	1.74	15.62	0.24	14.62	10.48	0.44	0.00	0.06	96.06
		52.53	0.17	1.33	17.46	0.30	13.17	10.87	0.36	0.00	0.08	96.27
150R-1, 81-83	1427.2	51.64	0.18	2.48	16.66	0.24	12.05	12.47	0.22	0.00	nd	95.94
152R-1, 5-8	1436.0	51.22	0.53	3.92	14.05	0.00	15.48	10.70	1.07	0.00	0.12	97.09
2000 000 000 000 000 000 000		49.67	0.42	4.26	16.22	0.29	13.11	10.45	0.88	0.00	0.09	95.39
152R-1, 17-19	1436.1	51.43	0.72	5.23	13.05	0.24	15.81	10.57	0.91	0.03	nd	97.99
152R-1, 61-64	1436.5	52.97	0.14	4.34	19.10	0.40	10.17	9.42	0.19	0.06	nd	96.79
153R-1, 77-79	1446.1	50.76	0.20	3.54	19.08	0.31	11.31	11.05	0.28	0.03	nd	96.56
		50.85	0.31	1.88	26.90	0.35	8.79	7.68	0.43	0.08	nd	97.27
154R-1, 116-119	1455.5	46.40	0.35	3.65	28.86	0.76	5.99	10.22	0.60	0.06	nd	96.89
		48.37	0.41	3.47	31.44	0.65	5.12	8.58	0.48	0.14	nd	98.66
156R-1, 37-39	1464.2	51.18	0.31	1.97	22.14	0.77	9.08	12.08	0.23	0.00	nd	97.76
157R-1, 1-6	1473.1	51.01	0.49	4.20	13.91	0.17	15.62	10.66	0.79	0.06	nd	96.91
		51.73	0.47	4.24	15.51	0.43	15.80	8.75	0.62	0.00	nd	97.55
157R-1, 2-5	1473.1	52.79	0.15	1.79	12.82	0.25	16.02	10.99	0.49	0.00	0.08	95.38
		50.81	0.34	3.54	13.57	0.28	15.32	10.40	0.85	0.00	0.09	95.20
1000 1 40 40		49.78	0.51	4.24	14.54	0.23	14.52	10.37	0.85	0.00	0.11	95.15
15/R-1, 60-63	1473.7	53.03	0.11	1.33	21.78	0.59	9.87	11.79	0.12	0.02	nd	98.64
150D 1 16 10	1400.7	51.47	0.26	3.58	18.20	0.33	13.24	8.64	0.49	0.00	na	90.21
1368-1, 10-18	1402.7	51.07	0.16	2.09	17.58	0.17	14.72	10.44	0.30	0.00	0.09	90.79
158R-1 18-20	1482 7	51.50	0.50	4 15	16.04	0.17	13.04	11.53	0.40	0.00	nd	98.50
158R-1, 30-34	1482.8	50.28	0.39	3.62	16.11	0.29	13.04	10.78	0.38	0.00	nd	95.07
100111, 00 01	140210	53.14	0.25	2.52	18.52	0.29	13.80	8.71	0.37	0.03	nd	97.63
158R-1, 32-34	1482.8	51.86	0.16	4.92	15.72	0.22	15.53	8.24	0.88	0.00	0.09	97.62
159R-1, 27-29	1488.4	52.77	0.16	3.14	15.03	0.28	13.90	11.71	0.41	0.01	nd	97.41
159R-1, 52-56	1488.6	47.50	0.44	3.93	24.97	0.32	7.36	10.41	0.58	0.03	nd	95.54
		48.15	0.21	2.75	29.52	0.43	7.14	7.32	0.60	0.01	nd	96.13
160R-1, 25-27	1495.0	51.21	0.61	2.68	15.31	0.00	13.69	11.40	0.52	0.07	nd	95.49
		48.17	0.35	3.67	27.85	0.56	7.46	7.46	0.44	0.03	nd	95.99
160R-1, 59-60	1495.3	51.55	0.50	3.56	17.85	0.24	13.31	10.13	0.59	0.02	nd	97.75
164R-1, 55-58	1515.7	51.99	0.55	3.17	17.31	0.33	13.35	10.62	0.39	0.02	nd	97.73
		49.73	0.76	5.07	14.90	0.29	15.82	8.72	0.89	0.05	nd	96.23
165R-1, 72-76	1530.2	48.68	0.63	3.79	23.76	0.09	8.29	9.38	0.54	0.16	nd	95.32
1000 1 00 01	10100	49.22	0.42	3.01	27.09	0.22	8.41	7.72	0.50	0.13	nd	96.72
169K-1, 28-31	1547.9	50.98	0.75	4.73	15.33	0.25	16.38	8.99	0.69	0.01	nd	98.11
1/0K-1, 49-53	1554.1	52.16	0.27	4.14	18.12	0.29	12.14	10.94	0.44	0.02	nd	96.81
		55.10	0.20	2.05	15.34	0.37	15.04	9.22	0.33	0.01	nu	90.34
Actinolitic Ca-amphib	ole with S	1 > 7.25	and (Ca	+ Na)B	< 1.34							
142R-1, 2-4	1352.8	53.09	0.33	3.02	18.13	0.30	14.87	7.43	0.27	0.03	nd	97.47
142R-2, 73-75	1355.0	52.32	0.12	4.47	20.38	0.53	14.22	5.58	0.43	0.02	nd	98.07
144R-1, 43-47	1369.1	51.93	0.06	5.14	17.25	0.31	17.69	5.02	0.43	0.01	nd	97.84
147R-2, 30-33	1399.2	49.69	0.24	2.46	29.82	0.75	8.50	4.48	0.37	0.03	nd	96.34
153R-1, 77-79	1446.1	47.56	0.33	4.64	28.66	0.37	8.08	7.17	0.46	0.12	nd	97.39
158R-1, 32-34	1482.8	50.72	0.06	3.92	19.20	0.26	13.87	7.08	0.48	0.00	0.09	95.68
160R-1, 59-60	1495.3	50.79	0.39	1.93	23.22	0.45	11.99	7.52	0.28	0.00	nd	96.57
105K-1, /2-/6	1530.2	51.39	0.22	3.17	21.57	0.46	13.99	5.27	0.36	0.00	nd	90.43

rable o (continueu).	Tab	le 8	(continued)	).
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Core, section, interval (cm)	Depth (mbsf)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO ^a	MnO	MgO	CaO	Na ₂ O	к ₂ 0	CI	Total
Hornblendic Ca-amph	ibole with	si < 7.	25 and (0	Ca + Na)	B > 1.3	4						
142R-1, 118-121	1354.0	44.29	3.21	9.52	11.55	0.24	14.69	9.76	3.87	0.06	nd	97.19
	2.500 202 A	41.90	0.13	14.29	16.83	0.37	13.77	8.52	1.76	0.02	nd	97.59
145R-3, 137-138 13	1384.2	42.34	1.43	17.95	14.24	0.38	8.73	10.77	2.26	0.08	nd	98.18
		45.76	1.00	7.87	16.64	0.17	15.42	9.82	1.32	0.08	nd	98.08
152R-1, 5-8	1436.0	47.06	0.73	7.87	11.38	0.13	15.38	10.73	1.87	0.13	0.13	95.41
152R-1, 17-19	1436.1	48.47	0.63	8.86	11.74	0.20	15.63	10.97	1.46	0.03	nd	97.99
159R-1, 52-56	1488.6	42.33	0.91	9.03	28.18	0.49	5.54	7.16	2.05	0.05	nd	95.74
163R-1, 135-138	1513.0	45.26	1.52	10.37	13.21	0.10	14.24	10.36	2.41	0.03	nd	97.50
164R-1, 55-58	1515.7	46.94	0.94	6.93	13.66	0.28	15.60	10.16	1.10	0.05	nd	95.66
169R-1, 28-31	1547.9	44.15	1.81	13.24	11.50	0.12	12.96	11.18	1.78	0.13	nd	96.87
170R-1, 49-53	1554.1	44.26	0.07	13.25	15.05	0.18	13.21	8.62	1.92	0.00	nd	96.56
Hornblendic Ca-ampl	ibole with	n Si < 7.	25 and (0	Ca + Na)	B < 1.3	4						
142R-1, 2-4	1352.8	45.61	0.18	9.03	17.90	0.22	17.83	5.89	0.25	0.04	nd	96.95
144R-1, 43-47	1369.1	49.00	0.38	6.33	18.38	0.35	16.86	7.09	0.20	0.00	nd	98.59
156R-1, 37-39	1464.2	47.34	0.22	7.93	20.10	0.28	12.83	7.84	0.17	0.01	nd	96.72

Note: nd = not determined. Si, Ca, and Na were calculated on the basis of O = 23. ^a Total iron as FeO.



Figure 7. Frequency distribution of (Ca + Na)B values for amphibole.

The mineral paragenesis of Figure 10D, which is characterized by the mineral assemblage of prehnite-actinolite-epidote (+ chlorite, + albite and/or oligoclase, + quartz, + sphene), has been generally assumed to belong to the greenschist facies. However, the recent experimental study of a model basaltic system by Liou et al. (1985a) showed that the critical mineral assemblage of Figure 10D (prehnite-actinolite-epidote) can be seen to occupy a large pressure-temperature field transitional from the zeolite or prehnite-pumpellyite to greenschist facies at low pressures. In the literature, the mineral assemblage of Figure 10D has been reported from low-pressure-type metamorphic terrains such as the Tanzawa Mountains (Seki et al., 1969; Arai, 1987), Karmutsen volcanics (Kuniyoshi and Liou, 1976), Del Puerto ophiolite (Evarts and Schiffman, 1983), and Horokanai ophiolite (Ishizuka, 1985). From these facts, Liou et al. (1985a) proposed the prehnite-actinolite facies to describe this assemblage. In this study, this facies is adopted to denote the mineral

assemblage of Figure 10D, although there are some uncertainties about the reactions defining the transition from zeolite to the prehnite-actinolite facies, especially about the zeolite-out and actinolite-in reactions. The type (3) mineral assemblage may be a partial mineral assemblage of the prehnite-actinolite facies.

Previous studies on the alteration of Hole 504B showed that the mineral facies of the sheeted dike complex reached the greenschist facies (Alt et al., 1985, 1986). The present study reveals that prehnite is a common secondary mineral coexisting with actinolite, chlorite, and/or epidote, indicating that the temperature did not reach the reaction leading to the disappearance of prehnite, for example, prehnite + chlorite + quartz = clinozoisite + tremolite + fluid; this reaction defines the upper stability of the prehnite-actinolite facies. It follows that the mineral facies attained even in the deepest level of Hole 504B reached the prehnite-actinolite facies and not the greenschist facies in the sense of Liou et al. (1985a).



Figure 8. Variation of Si content against the Mg/(Mg + Fe) ratio for Ca amphiboles with (Ca + Na)B > 1.34. TR = tremolite; AT = actinolite; FAT = ferroactinolite; TRHB = tremolitic hornblende; ATHB = actinolitic hornblende; FATHB = ferroactinolitic hornblende; MHB = magnesiohornblende; FHB = ferrohornblende; TSHB = tschermakitic hornblende; FTSHB = ferrotschermakite.



Figure 9. Variation of Ca content against (Mg + Fe) values for amphibole.

## CONCLUSIONS

Alteration of the basalts recovered from Hole 504B during ODP Leg 111 is characterized by (1) lack of evidence for strong shear stress and widespread penetrative deformation, and, hence, good preservation of the primary (igneous) structures and textures; (2) partial to total replacement of primary olivine, plagioclase, and clinopyroxene by secondary minerals and the extensive to incipient development of secondary minerals in veins, fractures, vugs, or breccia matrix; and (3) the occurrence of the low-variance mineral assemblages laumontite + prehnite + epidote and prehnite + actinolite + epidote, both of which include chlorite, albite and/or oligoclase, quartz, and sphene. The mineral paragenesis described in terms of the model basal-

Core, section, interval (cm)	Depth (mbsf)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO ^a	MnO	MgO	CaO	Na ₂ O	Total
Sodic augite										
152R-1, 61-64	1436.5	49.09 51.88	0.57 0.01	5.12 0.69	10.77 17.02	0.17 0.34	11.06 9.32	21.29 19.23	0.64 2.06	98.71 100.55
		49.84	2.47	3.34	9.09	0.20	13.79	19.77	0.90	99.40
153R-1, 77-79	1446.1	52.27 50.65	0.03 0.03	0.63 0.24	15.00 19.83	0.42 0.38	10.63 8.26	20.10 19.29	1.66 0.14	100.74 98.82
Sphene										
CONSERVATION AND IN										
142R-1, 2-4	1352.8	30.34	36.28	2.04	0.95	0.00	0.00	27.04	0.02	96.67
142K-1, 118-121	1354.0	30.85	36.71	1.81	0.78	0.00	0.13	27.24	0.04	97.56
14/K-2, 30-33	1399.2	31.09	29.16	6.44	1.44	0.02	0.03	27.23	0.00	95.41
155K-1, //-/9	1440.1	30.05	33.24	3.02	2.12	0.01	0.00	27.49	0.01	90.90
154R-1 116-119	1455 5	31 15	34.25	3.00	1 32	0.07	0.00	27.95	0.02	97.60
1348-1, 110-115	1455.5	30.37	37 71	1 35	1.00	0.05	0.00	27 62	0.00	98.13
158R-1, 18-20	1482.7	30.61	35.61	2.36	1.66	0.04	0.05	27.62	0.04	97.99
158R-1, 30-34	1482.8	30.68	36.47	1.33	0.73	0.00	0.01	27.87	0.00	97.09
		31.09	36.47	2.52	1.10	0.00	0.02	27.02	0.02	98.24
159R-1, 52-56	1488.6	30.84	35.25	2.70	1.63	0.00	0.04	27.59	0.08	98.13
		30.06	37.01	2.09	1.46	0.01	0.07	27.03	0.01	97.74
160R-1, 25-27	1495.0	30.70	34.72	2.25	1.11	0.00	0.04	27.46	0.02	96.30
		31.10	34.12	4.12	0.97	0.00	0.02	27.67	0.02	98.02
160R-1, 59-60	1495.3	30.93	36.20	2.38	1.09	0.00	0.07	27.56	0.00	98.23
		31.01	35.21	2.58	1.46	0.00	0.00	27.06	0.01	97.33
170R-1, 49-53	1554.1	30.53	33.85	2.77	1.99	0.06	0.10	27.10	0.08	96.48
<b>T</b> -1-		29.10	50.25	1.04	0.94	0.00	0.05	27.44	0.01	10.27
Taic										
142R-2, 73-75	1355.0	56.97	0.00	2.60	9.72	0.00	23.21	0.49	0.03	93.02
144R-1, 43-47	1369.1	59.59	0.00	0.26	3.46	0.05	26.38	0.02	0.01	89.77
		54.42	0.06	4.24	9.04	0.00	24.26	1.18	0.04	93.24
159R-1, 27-29	1488.4	59.03	0.03	0.37	2.99	0.00	30.19	0.13	0.00	92.74
		61.05	0.00	0.18	5.07	0.06	28.40	0.00	0.03	94.79
170R-1, 49-53	1554.1	58.70	0.01	1.36	2.56	0.00	29.81	0.27	0.10	92.81
		56.67	0.04	2.85	6.76	0.04	25.29	0.26	0.01	91.92
Anhydrite										
152R-1, 17-19	1436.1	0.00	0.00	0.00	0.00	0.00	0.01	39.65	0.00	39.66
1021(1, 17 17	1450.1	0.00	0.00	0.00	0.00	0.04	0.00	38 79	0.00	38.83
152R-1, 61-64	1436.5	0.00	0.02	0.03	0.03	0.00	0.00	37.76	0.00	37.84
0.0000000000000000000000000000000000000	0.02/23/2	0.00	0.00	0.00	0.09	0.00	0.01	38.97	0.00	39.07
Pyrite										
144D 1 42 47	1260 1	0.04	0.04	0.00	(0.42	0.00	0.07	0.01	0.20	60.90
144K-1, 43-47	1426 1	0.04	0.04	0.00	50.63	0.00	0.07	0.01	0.30	60.09
152R-1, 17-19	1436.5	0.00	0.01	0.01	60.80	0.00	0.04	0.00	0.30	61 36
159R-1, 52-56	1488.6	0.00	0.04	0.03	59.00	0.00	0.03	0.00	0.16	59.26
169R-1, 28-31	1547.9	0.02	0.01	0.02	60.20	0.07	0.04	0.04	0.22	60.62
Chalcopyrite										
		0.01					0.10	0		
143R-1, 108-112	1360.4	0.01	0.06	0.05	41.93	0.03	0.10	0.11	0.44	42.73
147R-2, 30-33	1399.2	0.03	0.10	0.00	40.15	0.00	0.00	0.09	0.54	40.91
156R-1, 37-39	1464.2	0.00	0.03	0.00	39.68	0.00	0.00	0.07	0.03	39.81
159R-1, 52-56	1488.6	0.09	0.18	0.06	39.09	0.05	0.00	0.08	0.20	39.75
169R-1, 28-31	1547.9	0.11	0.03	0.00	44.32	0.03	0.02	0.06	0.23	40.54
Fe-Ti oxide										
			10.51				0.00		0.00	00.00
142R-2, 73-75	1355.0	0.15	19.51	1.71	70.76	1.03	0.05	0.15	0.00	93.36
		0.13	21.02	1.84	66.02	1.00	0.01	0.08	0.00	91.82
144P 1 42 47	1260 1	2.90	10.07	1.20	62.57	2.03	0.73	3 27	0.00	93.38
144R-1, 43-4/ 145R-3 137-129	1384 2	5.24	28 44	1.91	53 67	3.18	1.00	3.27	0.00	95.07
149R-2 50-53	1418 9	1 27	23.94	0.03	61 66	0.58	0.04	2 98	0.00	90.74
159R-1 27-29	1488 4	3.25	18 21	2 93	68 35	1.49	1.07	0.33	0.00	95 63
159R-1, 52-56	1488.6	1.54	27.15	1.38	64.92	1.08	0.16	0.02	0.00	96.25
		0.30	19.39	1.11	70.36	1.09	0.53	0.10	0.00	92.88
		0.23	11.19	1.52	77.00	0.49	0.04	0.27	0.00	90.74

Table 9. Representative analyses of sodic augite, sphene, talc, anhydrite, pyrite, chalcopyrite, and Fe-Ti oxide, Hole 504B, ODP Leg 111.

^a Total iron as FeO.



Figure 10. A. Compositions of actinolite, laumontite, epidote, prehnite, and chlorite in the tetrahedron  $2Al-2Fe^{3+}-(Fe^{2+}, Mg)-Ca.$  B. Projection of these phases from chlorite composition onto an A(2Al)-F(2Fe³⁺)-C(Ca) diagram. C and D. Mineral parageneses and compositional variations for type (6) and (7) mineral assemblages in the AFC projections, respectively. Lm = laumontite; Ep = epidote; Pr = prehnite; Chl = chlorite; and Act = actinolite.

tic system reveals that the basalts underwent zeolite facies to prehnite-actinolite facies alteration. In a strict sense, the mineral assemblage of the greenschist facies is not found in the samples examined here, suggesting that the temperatures of the greenschist facies  $(350^{\circ}-400^{\circ}C \text{ inferred from fig. 4 of Liou et al., } 1985a)$  were not attained in the deepest portion of Hole 504B.

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