4. ZEOLITE-FACIES METAMORPHISM OF CENTRAL KERGUELEN PLATEAU BASALTS¹

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ABSTRACT

Ocean Drilling Program Leg 120 recovered basement samples that consisted of zeolite-facies metabasalts at Sites 747, 749, and 750 on the Kerguelen Plateau. These basalts were metamorphosed in the low to intermediate zones of the zeolite facies, as indicated by the presence of diagnostic zeolites and the absence of chlorite, epidote, prehnite, pumpellyite, and wairakite. Chabazite, natrolite, thompsonite, mesolite, stilbite, huelandite, and smectites occur as amygduloidal fillings in basalts from Holes 747C and 750B, whereas only stilbite, laumontite, and pure and mixed-layered smectites were identified in amygduloidal basalts from Hole 749C. In the lower sections of Hole 749C, only laumontite and mixed-layered smectites coexist.

Based on calculations with published experimental phase equilibria, the absence of wairakite in basalts from Hole 749C and of laumontite in basalts from Holes 747C and 750B suggests that metamorphic temperatures did not exceed approximately 225° and 120°C, respectively. The presence of well-developed zeolite mineral assemblages and the absence of carbonate and clay mineral assemblages restricts X_{CO_2} in the fluid to approximately ≤ 0.0075 . Low- to intermediate-zone zeolite-facies mineral assemblages in basalts from the Kerguelen Plateau can be accounted for by metamorphism in an active geothermal area such as present-day Iceland.

INTRODUCTION

The zeolite facies is a low-temperature metamorphic facies characterized by mineral assemblages that consist of a diverse suite of zeolites and clays (e.g., Coombs, 1954; Zen and Thompson, 1974). Zeolite-facies metamorphic mineral assemblages are common in active geothermal areas and in shallow burial sequences. Field studies and experimentally calibrated mineral reactions have shown that the stability of zeolites and clays is sensitive to temperature, fluid activity, and bulk composition.

Basaltic basement was retrieved at Sites 747, 749, and 750 on the Kerguelen Plateau by Ocean Drilling Program (ODP) Leg 120 (Fig. 1). Results from preliminary shipboard studies indicate that the basalts constituting this large suboceanic plateau were metamorphosed in the zeolite facies. The present study was undertaken to provide a more detailed examination of the zeolite-facies mineral assemblages and to estimate temperatures and fluid conditions attending metamorphism. This paper confirms shipboard studies and provides the first detailed study of zeolite-facies metamorphism of a large suboceanic plateau.

NATURE OF THE BASALTS AND STRATIGRAPHIC RELATION TO OVERLYING SEDIMENTS

Shipboard studies (Schlich, Wise, et al., 1989) demonstrate that the basement is composed of a series of basalt flows of variable thicknesses and degrees of alteration. Geochemical and petrologic studies (Schlich, Wise, et al., 1989; Salters et al., this volume; Storey et al., this volume) have shown that the basalts consist of transitional olivine-normative tholeiites. The important mesoscopic features of these basalts and their stratigraphic relations to the overlying sediments are summarized below.

At Site 747, basalt flows are unconformably overlain by Coniacian nannofossil chalk at a depth of 296.6 m below seafloor (mbsf) (Fig. 1). Approximately 54 m of basalt was cored with 38% recovery. Contact relations and shallow resistivity and gamma-ray logs suggest that the basalts are comprised of many thin flows. An important feature of basalts from Site 747 is the occurrence of oxidized flow tops, which have been interpreted to indicate eruption in a subaerial environment.

Early Eocene nannofossil ooze and chert unconformably overlie basalt at 202 mbsf at Site 749 (Fig. 1). About 47.5 m of basalt was cored with 49% recovery. The basalts consist of flows with altered, amygduloidal flow tops that grade into fresher, more massive basalts downhole.

At Site 750, silty to calcareous claystone of Albian age overlies basalts at 675.5 mbsf (Fig. 1). Approximately 34 m of basalt was cored with 67% recovery. Basalts at this site consist of a highly altered upper section and a moderately altered lower section.

AGE OF THE BASEMENT AND TIMING OF METAMORPHISM

Basalts at Site 750 are overlain by middle Albian sediments and therefore have a minimum age of 100 Ma. Based on conventional K-Ar and ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ whole-rock analyses, Whitechurch et al. (this volume) have shown that the Kerguelen Plateau was formed by 110 Ma. This age determination is consistent with stratigraphic constraints and with a plagioclase K-Ar age of 114 ± 1 Ma for a basalt dredged in the 77°E Graben (Bassias et al., 1987).

The timing of metamorphism is not well constrained. Conventional whole-rock K-Ar ages on altered basalts gives ages ranging from 76 \pm 6 to 80 \pm 3 Ma (Whitechurch et al., this volume). These ages probably reflect differential amounts of argon loss caused by hydrothermal alteration and have no real geologic significance. Shipboard X-ray diffraction (XRD) studies did not identify authigenic zeolites (e.g., phillipsite) in pelagic sediments overlying the basalts in Hole 750B (Schlich, Wise, et al., 1989). The apparent absence of zeolites in the

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Figure 1. Map of the Kerguelen Plateau showing stratigraphic relations and the location of Sites 747, 749, and 750. Kerguelen and Heard Islands and the 2000- and 3500-m bathometric contours are shown for reference. Bathymetry from Schlich et al. (1987).

overlying sediments indicates that metamorphism of the basalts took place before the middle Albian and was probably coeval with extrusion. However, until detailed studies of these sediments are made, this constraint on the timing of metamorphism remains uncertain.

PETROGRAPHY OF SECONDARY MINERALS

All basalts recovered from Leg 120 are altered. The degree of alteration varies from a few percent to nearly 100%. Zeolites are confined to amygdules, whereas green and brown clays and calcite are present in the amydgules, groundmass, and veinlets. The amygdules contain one or more zeolites, vary in size from about 2 mm to 3 cm, and range in shape from circular to highly irregular (Fig. 2).

Secondary minerals from amygdules were identified by means of the following procedure. Specimens were cut to dissect the amygdules. The amygdule filling from one half of the specimen was powdered and analyzed with standard XRD methods. An electron microprobe mount was prepared from the remaining half. These mounts were examined optically, and the zeolites and clays were analyzed with the electron microprobe. A summary of the secondary minerals identified in Leg 120 basalts is given in Table 1.

Different secondary mineral assemblages distinguish basalts from Hole 749C from Holes 747C and 750B (Table 1). Basalts from Hole 747C contain chabazite, natrolite, thompsonite, mesolite, stilbite, huelandite, calcite, and smectites. Basalts from Hole 750B contain chabazite, huelandite, stilbite, and smectites. Stilbite, laumontite, calcite, and pure and mixed-layer smectites were identified in Hole 749C. The lower sections of Hole 749C contain only laumontite, calcite, and smectites.

Chabazite appears as a white to reddish mineral with a pseudocubic morphology and perfect 90° cleavage. Chabazite occurs with or without natrolite, thompsonite, mesolite, or huelandite in Holes 747C and 750B (Figs. 2A and 2B). Huelandite appears as large brick-red crystals with or without chabazite. Stilbite is present in the lower sections of Holes 747C and 750B and in the upper sections of Hole 749C (Table 1). Stilbite crystals are translucent to white and commonly appear as large, randomly oriented (Fig. 2D) or sheaflike aggregates. Laumontite appears as small, white to light yellow, randomly oriented crystal aggregates with or without stilbite and calcite (Figs. 2C and 2D). Natrolite, thomsonite, and mesolite are less common and were identified only in Hole 747C. Natrolite and thomsonite are present as radiating, very fine to fine prismatic, white needles (Fig. 2A). Mesolite occurs as dark-colored radial crystals associated with chabazite (Fig. 2B).

Calcite is generally not present in the amygduloidal basalts from Holes 747C and 750B. Calcite is present in amygdules from basalts in Hole 749C; however, it is associated with stilbite and laumontite (Figs. 2C and 2D). In most of the samples examined, however, textural observations suggest that calcite is secondary in origin with respect to the zeolites (Fig. 2C). In a few samples, the textural relations are unclear as to the relative timing of calcite and zeolite crystallization (Fig. 2D). In these samples, calcite may have coexisted with laumontite with or without stilbite.

Green and brown clays are present in most basalts (Table 1). Clays occur as amygdule rims (Figs. 2A and 2B) and as alteration products after olivine and ilmenite. Rarely, green clays are associated with zeolites and calcite in amygdules (Fig. 2C). Petrographic studies indicate that chlorite, prehnite,



Figure 2. Photomicrographs of amygdules in altered basalts. Mineral abbreviations are given in Table 1. A. Sample 120-747C-16R-3, 76–78 cm (KP23): complex, clay-lined, amygdule with large chabazite crystals and radiating, fine prismatic crystals of natrolite and radiating tabular crystals of thompsonite; crossed nichols, width of field of view (wfv) = 4.0 mm. B. Sample 120-747C-16R-3, 109–112 cm (KP24): light-colored chabazite with 90° cleavages and dark-colored mesolite in a clay-lined amydgule; crossed nichols; wfv = 3.8 mm. C. Sample 120-749C-12R-1, 111–115 cm (KP26): laumontite + calcite + clay-filled amydgule; plane-polarized light; wfv = 3.0 mm. D. Sample 120-749C-15R-5, 143–147 cm (KP28): stilbite + laumontite + calcite-filled amydgule; later generations of laumontite and stilbite cut earlier calcite crystals; plane polarized light; wfv = 3.5 mm.

Core section	Lab number	Secondary minerals								
interval (cm)		Cbz	Ntr	Tmp	Mes	Stb	Hul	Lmt	Cal	Clay
120-747C-										
11R-2, 112-114							x			x
14R-1, 102-104	KP21	X			x					
15R-1, 68-70		X					x			x
15R-2, 8-9				x					X	X
15R-4, 3-6		x								X
16R-1, 71-75	KP22						x			X
16R-3, 76-78	KP23	х	X	х			0.5.55			x
16R-2, 2-5					X	X			х	
16R-3, 13-14						x				X
16R-3, 109-112	KP24	x								х
120-749C-										
12R-1, 111-115	KP26							х	X	x
12R-2, 137-139						х			X	X
15R-5, 143-147	KP28					X		х	X	
15R-6, 25-28	KP38					X		0.001		X
15R-6, 102-106	KP28B							х		
15R-6, 120-122								X	X	X
16R-1, 74-79	KP29							x		x
16R-4, 36-38	KP30							X		x
16R-4, 45-46								X	X	x
16R-4, 64-69	KP37							х	x	х
120-750B-										
15R-1, 14-15		x								
15R-1, 103-105	KP31	x								X
17R-2, 61-63	KP35						х			x
17R-3, 43-45	KP36					x			x	х

Table 1. Summary of secondary minerals identified in Central Kerguelen Plateau basalts, Leg 120.

Notes: Laboratory number labeled "-" indicates shipboard indentification. Cbz = chabazite, Ntr = natrolite, Tmp = thompsonite, Mes = mesolite, Stb = stilbite, Hul = huelandite, Lmt = laumontite, and Cal = calcite.

pumpellyite, epidote, sphene, and wairakite were not stable phases in the groundmass or amygdules of the metabasalts.

ANALYTICAL METHODS

Zeolites (Table 2) and clays (Table 3) were analyzed with an ARL-SEMQ, eight-channel, wavelength-dispersive electron microprobe at The University of Calgary. Electron microprobe mounts were prepared with room-temperature-cured epoxy to avoid water loss from heating. The microprobe was operated with an accelerating potential of 15 kV, $300-\mu A$ emission current, 100-nA beam current, a large ($12 \mu m$) defocused beam, and a 20-s counting time.

Scans of net intensity vs. time revealed no loss of Na (the most volatile element) during 20 s of counting. Zeolites and clays were analyzed with a moving beam and therefore represent integrated analyses. Mineral analyses report the mean of five integrated analyses. Natural feldspars and synthetic glass standards were used for all elements except Fe and Mg. Clinopyroxene standards were used for Fe and Mg.

Data were reduced according to the correction procedures of Bence and Albee (1968) using the empirical alpha factors of Albee and Ray (1970). Zeolite analyses are reported on an anhydrous basis. Water in the clays was estimated by difference and iteration. The *E* factor of Gottardi and Galli (1985) was used to confirm the reliability of the analyses. The *E* factors between 0% and 10% are considered acceptable analyses. With the exception of chabazites from Sample 120-747C-16R-3, 109-112 cm, *E* factors of 3.9% or better were obtained (Table 2).

MINERAL CHEMISTRY

The zeolites form a group of hydrated aluminosilicates with molecular Al:(Ca, Sr, Ba, Na, K) equal to 1 and O:(Al + Si)

equal to 2. The solid substitution of alkaline (Na and K) and alkaline earth elements (Ca, Sr, and Ba) generally involves a change in the Si/Al ratio. Many zeolites show variations from stoichiometric proportions. These variations can be expressed as deviations from ideal Si/Al and Na/Ca ratios (Table 2).

Chabazites deviate from the stoichiometric Si/Al ratio (i.e., 2.0) with ratios ranging from 1.9 (Sample 120-747C-16R-3, 76–78 cm) to 2.5 (Sample 120-750B-15R-1, 103–105 cm). Extensive substitution of Na and K for Ca has taken place, with Na and K accounting for up to 2.3 and 0.80 atoms per unit cell, respectively. The chabazites could be classified as herschelites because Na > Ca (Mason, 1962).

Natrolite was the only zeolite analyzed that is essentially pure and stoichiometric. Only very minor amounts of Ca, Fe, and K impurities are present. The stoichiometric nature of natrolite in Sample 120-747C-16R-3, 76–78 cm, is consistent with the work of Hey (1932), who has shown that natrolites typically exhibit a narrow range in composition.

Thompsonites from Sample 120-747C-16R-3, 76–78 cm, deviate significantly from their ideal formula, with respect to Si/Al and Na/Ca ratios. The Si/Al ratio is > 1 (i.e., 1.23), and considerable Na solid solution has occurred.

Stilbites in Sample 120-750B-17R-3, 43-45 cm, have nearly ideal Si/Al and Na/Ca ratios (ideal: Si/Al = 3.0 and Na/Ca = 0.25). In contrast, stilbites from Sample 120-747C-15R-5, 143-147 cm, have Si/Al and Na/Ca ratios that deviate some from the stoichiometric proportions. Stilbites from both of the above samples have minor amounts of K, Fe, and Mg impurities.

Laumontites in basalts from Hole 749C differ from the stoichiometric Si/Al ratio of 2, with Si/Al ratios ranging from 2.1 to 2.3. In these laumontites, considerable substitution of Na and K for Ca is evident, with Na and K comprising up to 2.9 and 2.4 atoms per unit cell, respectively. With the excep-

Table 2. Representative electron microprobe analyses of zeolites.

	Hole 747C			Hole 749C						Hole 750B						
	KP23 Cbz	Ntr	Tmp	KP24 Chz	KP26 Lmt Core	Lmt Rim	KP28 Stb	Lmt	KP28B Lmt Core	Lmt Rim	KP30 Lmt Core	Lmt Rim	KP31 Cbz	Cbz	KP36 Stb	Stb
SiO ₂ Al ₂ O ₃ FaO*	51.38 20.82	46.31 26.47	40.51 27.94	49.26 22.75	53.54 20.55	53.80 20.61	62.16 16.79	52.22 21.00	51.99 20.52	53.33 20.12	52.32 21.22	52.52 20.49	55.24 20.76	56.86 19.71	59.89 17.23	58.74 16.66
MgO CaO	<0.03	<0.03	<0.04 <0.03 9.27	0.04	<0.04	<0.04 <0.03	0.29	0.13	0.19	0.14	0.40	0.13	0.15	0.00	0.16	0.26
Na ₂ O K ₂ O	8.17 3.95	15.00	6.98	7.41	2.31	3.31	3.73	3.18	3.57	3.55	3.50	3.46	8.03	7.39	1.39	1.61
Sum Si	86.06 8.121	88.51 23.946	84.71 22.028	85.77 7.806	86.91 16.542	87.53 16.558	89.35 27.217	86.65 24.431	85.92 16.327	86.58 16.571	87.39 16.181	86.19 16.410	88.75 8.319	88.62 8.526	86.69 26.905	85.47 26.858
Al Fe	3.878 0.015	16.131 0.026	17.906 0.000	4.249 0.019	7.483 0.000	7.476 0.000	8.664 0.106	11.580 0.051	7.595 0.050	7.368 0.036	7.734 0.119	7.546	3.685 0.019	3.483 0.008	9.123 0.079	8.978 0.145
Mg Ca	0.000 0.276	0.000 0.360	0.000 5.401	0.009 0.555	0.000 2.291	0.000 1.870	0.170 2.472	0.091 2.973	0.075 2.076	0.042 1.988	0.194 1.995	0.056 2.066	0.038 0.452	0.058 0.413	0.107 3.648	0.177 3.708
Na K	2.504	0.013	7.359 0.007	2.277	1.384	1.975	3.167	2.885 2.423	2.174	2.139 1.340	2.099	2.096	2.345	2.149	0.132	0.146
Si/Al Na/Ca	2.09	2.45 1.48 41.77	-1.44 1.23 1.46	6.94 1.85 4.10	1.38 2.21 0.60	1.85 2.22 1.06	-1.75 3.14 1.28	1.71 2.11 0.97	-1.79 2.15 1.05	-2.06 2.25 1.08	2.09	-0.98 2.18 1.01	1.98 2.26 5.19	1.78 2.45 5.20	2.95 0.33	-3.64 2.99 0.39

Notes: Cbz = chabazite, Ntr = natrolite, Tmp = thompsonite, Lmt = laumontite, and Stb = stilbite. FeO* = total iron expressed as FeO. Core = amydgule center and Rim = amydgule rim. Number of ions based on 24 oxygens (chabazite), 48 oxygens (laumontite), 72 oxygens (stilbite), and 80 oxygens (natrolite and thompsonite). BaO < 0.14 wt% for all analyses. *IE* factor from Gottardi and Galli (1985).

tion of Sample 120-749C-12R-1, 111–115 cm, all of the laumontites contain minor amounts of Fe and Mg impurities.

No reliable analyses of helandites from Holes 747C and 750B were obtained. The E factors were generally in excess of 15%. Identification of heulandites is based entirely on optical properties and XRD patterns.

Based on shipboard XRD studies, clays from Holes 747C and 750B are composed of fairly pure smectites, whereas clays from Hole 749C consist of pure and interlayered smectites (Schlich, Wise, et al., 1989). These clays show a large range in composition (Table 3). Green clays filling amydgules in Samples 120-749C-12R-1, 111–115 cm, and -16R-4, 36–38 cm, are compositionally variable. Brown and green clays within Sample 120-750B-15R-1, 103–105 cm, are chemically distinct.

PRESSURE, TEMPERATURE, AND FLUID CONDITIONS ATTENDING ZEOLITE-FACIES METAMORPHISM

The quantitative determination of pressure (P), temperature (T), and fluid conditions attending zeolite-facies metamorphism is hampered by many complexities (Miyashiro and Shido, 1970; Zen and Thompson, 1974; Ghent and Miller, 1974; Ghent, 1979). These complexities include (1) the extensive solid solution of zeolites and the lack of solution models; (2) the question whether experimentally produced zeolites correspond chemically and structurally to natural zeolites; (3) the question of equilibrium at low T; and (4) the effect of fluid composition. Despite these complexities, however, as will be shown in this paper, good agreement is reached between Testimates determined from thermodynamic calculations and *in situ* T measurements from drill holes in an active geothermal area such as Iceland with similar zeolite mineral assemblages.

Pressure

Stratigraphic and tectonic considerations indicate that P must have been very low during the metamorphism of Kerguelen Plateau basalts. The thin sedimentary cover (Fig. 1) overlying the basaltic basement and the intraplate setting of the Kerguelen Plateau indicates that the basalts were never deeply buried, either stratigraphically or tectonically. If the basalts were erupted and metamorphosed in a subaerial environment, then the effective solid pressure (P_s) was on the order of a few bars. Assuming a pre-Cenozoic metamorphism, the maximum thickness of the sediments was 200 m (Fig. 1; Hole 750B), and the maximum P_s would have been about 35 bars, using measured densities from the overlying sediments (Schlich, Wise, et al., 1989).

The uncertainty in P_s is not crucial because zeolitic reactions have steep slopes on *P*-*T* diagrams and therefore are largely independent of *P*. Given this and the low P_s estimates, we can safely assume that *P* was not an important factor controlling zeolite paragenesis.

Temperature

Field studies and experimentally calibrated equilibria demonstrate that zeolite reactions are strongly T dependent. The absence of chlorite, epidote, prehnite, pumpellyite, and wairakite from the secondary mineral assemblage of Kerguelen Plateau basalts indicates that metamorphism was confined to the low and intermediate zones of the zeolite facies.

By using experimentally calibrated mineral equilibria, the absence of certain zeolites can be used to constrain maximum T for the lower zone mineral assemblages in Hole 750B and the higher zone mineral assemblages in Hole 749C. In the following calculations, it is assumed that $P_{fluid} = P_{H_2O} = P_s = 35$ bars and reactants and products are pure phases. The fugacity of H₂O was interpolated to lower P (i.e., 35 bars) using data from Burnham et al. (1969).

The absence of wairakite in basalts from Hole 749C allows us to use the reaction (Liou, 1971a)

$$aumonitite = wairakite + 2 H_2O$$
(1)

to estimate $T_{maximum}$ at this site. The equilibrium constant equation for Reaction 1, presented by Ghent and Miller (1974), gives $T_{maximum} = 225^{\circ}$ C.

The absence of laumontite in stilbite-bearing basalts from Hole 750B (Sample 120-750B-17R-3, 43-45 cm), suggests $T_{maximum} = 115^{\circ}$ C, using the experimentally calibrated reaction (Liou, 1971b)

stilbite = laumontite + 3 quartz + 3
$$H_2O_{2}$$
 (2)

Thompson (1971) has suggested that the reaction

huelandite = laumontite + 2 or 3 quartz + 2 H_2O (3)

is in equilibrium at a T of about 120°C at $P_{\rm H_{2}O} = 2000$ bars. At lower $P_{\rm H_{2}O}$, Reaction 3 is stable at lower T. Reaction 3 provides $T_{maximum}$ in good agreement with T from Reaction 2,

	Hole 747C				Hole 750B					
	KP23 Gm Grn	KP24 Gm Grn	KP26 Amg Grn	KP26 Amg Grn	KP28 Gm Grn	KP30 AmgR Grn	KP30 AmgR Grn	KP31 Gm Brn	KP31 Gm Grn	KP36 Gm Brn
SiO ₂	40.14	37.08	55.34	55.47	32.92	38.83	38.02	55.45	32.71	53.48
Al ₂ O ₃	14.93	12.17	1.91	2.02	10.82	9.47	9.38	23.64	15.70	23.23
FeO*	8.98	16.84	18.91	19.16	27.80	24.73	25.31	3.36	24.58	4.16
MgO	17.06	17.11	6.69	6.64	9.02	14.08	13.84	6.67	13.88	5.50
CaO	0.44	1.10	0.20	0.22	1.89	1.69	1.70	1.64	0.47	1.03
Na ₂ O	0.18	0.18	< 0.02	< 0.02	0.12	0.14	0.20	0.10	0.04	0.09
K ₂ Õ	0.33	0.32	8.89	9.02	0.12	0.21	0.21	0.59	0.03	0.24
$H_{2}O$	17.53	15.03	7.82	7.15	17.07	10.64	11.09	8.33	12.35	12.06
Sum	99.67	99.84	99.77	99.69	99.76	99.79	99.75	99.78	99.76	99.79
Si	5.715	5.420	7.595	7.576	5.315	5.621	5.568	6.614	4.847	6.641
Al	2.505	2.097	0.309	0.325	2.059	1.616	1.619	3.323	2.742	3.400
Fe	1.069	2.059	2.170	2.189	3.753	2.994	3.100	0.335	3.046	0.432
Mg	3.620	3.728	1.368	1.352	2.171	3.038	3.021	1.186	3.065	1.018
Ca	0.067	0.172	0.029	0.032	0.327	0.262	0.267	0.210	0.075	0.137
Na	0.050	0.050	0.000	0.000	0.038	0.039	0.057	0.023	0.011	0.022
K	0.060	0.062	1.556	1.572	0.025	0.039	0.039	0.090	0.006	0.038
OH	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000

Table 3. Representative electron microprobe analyses of clays.

Notes: Grn = green clay, Brn = brown clay, Amg = amydgule, AmgR = amydgule lining, and Gm = groundmass. FeO* = total iron expressed as FeO. Number of ions based on 20 oxygens, 4 OH. BaO < 0.14 wt% in all analyses.

suggesting that metamorphism of basalts from Holes 747C and 750B took place at \leq 120°C.

The *T* estimates determined using experimental data have a high degree of uncertainty as a result of the factors affecting these equilibria. For example, if $P_{\rm H_2O} < P_s$; or if the fluid phase was diluted by other components such as CO₂, NaCl, or S; or if $P_s < 35$ bars, then the above *T* estimates would be lower. On the other hand, solid solution in the zeolites will expand the stability field of zeolites. It is possible that these factors effectively cancel each other and that the *T* estimates based on experimental equilibria are reasonably accurate.

Fluid Composition

Thompson (1971) has calculated phase relations involving zeolites in equilibrium with a binary H_2O-CO_2 fluid. His work has shown that laumontite is stable with respect to calcite, clays, and quartz if $X_{CO_2} < 0.0075$ (for $P_{total} = P_{fluid} = 2000$ bars). At lower pressures, laumontite is stable at lower X_{CO_2} values. Thompson (1971) showed that, in general, the presence of zeolites, and not the assemblage carbonate and clay, restricts the fluid to low X_{CO_2} values (i.e., <0.0075).

GEOTHERMAL ACTIVITY AND COMPARISON OF ZEOLITE ASSEMBLAGES FROM THE KERGUELEN PLATEAU WITH THOSE FROM ICELAND

The zeolite-facies mineral assemblages identified in basalts from the Kerguelen Plateau probably precipitated from hydrothermal solutions at elevated temperatures in an active geothermal field. This has been determined from an examination of cores, petrographic observations, mineral chemistry, and the insufficient sedimentary cover necessary to produce sufficient temperatures for burial metamorphism. For this reason, it is reasonable to compare zeolite mineral assemblages documented in Iceland with those developed in Kerguelen Plateau basalts because (1) geochemical and isotopic data (Salters et al., this volume; Storey et al., this volume) suggest that Iceland is a possible tectonic model for the Kerguelen Plateau, and (2) Iceland is the location of a transitional tholeiite-hosted modern geothermal field in which zeolite zones and T distributions in drill holes have been documented (Walker, 1960; Kristmannsdòttir and Tòmasson, 1978).

Five zeolite zones were recognized by extensive drilling in Icelandic geothermal areas (Krismannsdòttir and Tòmasson, 1978). Zone 1 contains chabazite and levyne; Zones 2 and 3 contain zeolites such as thomsonite, heulandite, and stilbite; Zone 4 is marked by the first appearence of laumontite and scattered occurrences of stilbite and heulandite; and Zone 5 contains wairakite and analcime. These zones have been calibrated against measured T in a series of drill holes: Zone 1 (up to 70°C), Zones 2 and 3 (70°-110°C), Zone 4 (110°-230°C), and Zone 5 (230°-300°C).

With respect to the Kerguelen Plateau, Holes 747C and 750B and Hole 749C are strikingly similar to Zones 1–3 and Zone 4 of Krismannsdottir and Tomasson (1978), respectively. Maximum T for Zones 3 and 4 in Iceland are 110°C and 230°C, respectively, which is in excellent agreement with calculated T estimates from Holes 747C and 750B (\leq 120°C) and Hole 749C (\leq 225°C).

CONCLUSIONS

Zeolite-facies mineral assemblages in amygdules from basement basalts recovered at Sites 747, 749, and 750 on the Kerguelen Plateau have been studied to characterize the grade of zeolite-facies metamorphism and the temperature and fluid conditions attending this metamorphism. The XRD and electron microprobe studies and the calculations made on the basis of experimental phase equilibria have shown that

1. basalts from Holes 747C and 750B contain a diverse zeolite mineral assemblage without laumontite, implying metamorphism in the lowest zeolite-facies zone at $T \le 120^{\circ}$ C;

2. basalts from Hole 749C contain laumontite without wairakite, epidote, or pumpellyite, implying that metamorphism occurred at an intermediate zeolite-facies zone ($T \le 225^{\circ}$ C); and

3. the rare occurrences of coexisting carbonate and clay assemblages in amygdules from basalts from all sites suggests that a low X_{CO_7} (≤ 0.0075) fluid attended metamorphism.

Given the geochemical and isotopic similarities between the Kerguelen Plateau and the Icelandic basalts, and similar zeolite-facies mineral assemblages, we propose that basalts from the Kerguelen Plateau underwent metamorphism as a result of hydrothermal alteration in an active geothermal area, such as seen in present-day Iceland.

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