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Pumpellyite from the oceanic crust, DSDP/ODP Hole 504B

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ABSTRACT

Pumpellyite has been found in doleritic basalt of a sheeted dyke complex drilled from 2072.1 m below sea floor in DSDP/ODP Hole 504B, south of the Costa Rica Rift, eastern Pacific. It occurs as fine-grained crystal aggregates accompanied by albite, chlorite and chalcopyrite, which partially replace a plagioclase phenocryst (An_{85-88}) that is also associated with primary magnetite. Chemical compositions of the pumpellyite vary antithetically in relation to Fe* and Al as well as Fe* and Mg, indicating the dominant substitution of Fe^{3+} by Al with the minor substitution of Fe^{2+} by Mg. Such compositional variations overlap with those of prehnite-pumpellyite facies rocks dredged from other oceanic ridges and intra-oceanic arcs, and those of similar facies rocks from ophiolites, but are aluminous compared with those of zeolite facies metabasites in ophiolites. These observations suggest that the breakdown of the plagioclase phenocryst and magnetite in the presence of a Cu- and S-bearing fluid phase led to the formation of pumpellyite + albite + chlorite + chalcopyrite during oceanic ridge hydrothermal alteration.

Keywords: DSDP/ODP Hole 504B, hydrothermal alteration, oceanic crust, pumpellyite.

Introduction

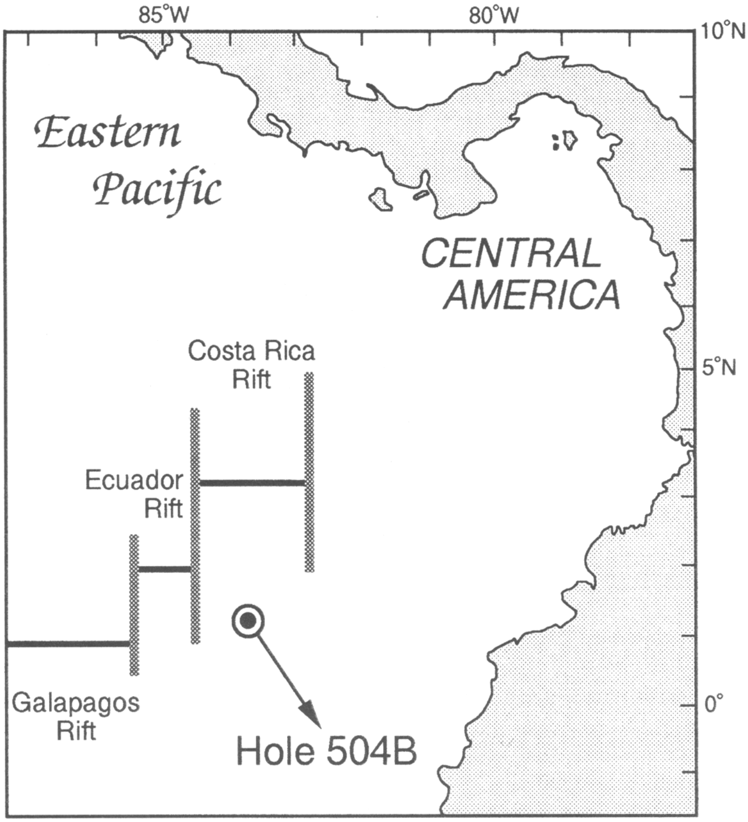
Pumpellyite often occurs in zeolite to prehnite-pumpellyite facies metabasites of ophiolitic sequences such as the East Taiwan ophiolite (Liou, 1979) and the Horokanai ophiolite in northern Japan (Ishizuka, 1991), which are considered to have suffered hydrothermal alteration in the vicinity of an oceanic ridge. However, pumpellyite is a rare mineral in altered rocks dredged or drilled from ocean-floor that was originally produced by oceanic ridge volcanism and subsequently underwent oceanic ridge hydrothermal alteration. Thus, only three occurrences of pumpellyite have been reported from the ocean-floor, namely the median valley at 22°N latitude (Melson *et al.*, 1968), the Vema fracture zone (Mevel, 1981) of the Mid-Atlantic Ridge, and the Garrett fracture zone of the East Pacific Rise (Bideau *et al.*, 1991). This is a problem for hypotheses invoking an oceanic ridge origin for hydrothermal alteration of ophiolite.

Also, pumpellyite has been described from zeolite to greenschist facies metabasites of the Del Puerto ophiolite (Ewarts and Schiffman, 1983) and from prehnite-pumpellyite facies rocks drilled from the Sumis Rift and Ohmachi Seamount, western Pacific (Yuasa *et al.*, 1993). These pumpellyite-bearing metabasites were derived from arc–forearc volcanic rocks and are interpreted to have been metamorphosed during the pre-rifting stage of an intra-oceanic arc. This implies that there is another candidate for the origin of ophiolite hydrothermal alteration, such as alteration in the vicinity of an intra-oceanic arc.

In the course of the petrographical work on the altered rocks recovered from ocean floor (Hole 504B), we have found pumpellyite which clearly formed by oceanic ridge hydrothermal alteration. The following is a petrographic description of the pumpellyite-bearing rock, along with a brief discussion of its petrological significance in hydrothermal alteration of the ocean floor as well as of ophiolite.

Hole 504B

Hole 504B is located ~200 km south of the Costa Rica Rift, eastern Pacific (Fig. 1), where the sea is 3460 m deep. It penetrates 5.9 Ma old oceanic crust. Three Legs (69, 70 and 83) of the Deep Sea Drilling Project (DSDP) and four Legs (111, 137,



G. 1. Location of DSDP/ODP Hole 504B, south of the Costa Rica Rift in the eastern equatorial Pacific (modified from Hobart *et al.*, 1985).

140 and 148) of the Ocean Drilling Program (ODP) have been devoted to Hole 504B, establishing the most complete reference section to date through the upper oceanic crust (Fig. 2). Coring during these Legs to 2111.0 m below sea floor (mbsf) revealed 274.5 m of sediment and then 571.5 m of pillow lavas and minor non-pillowed flows, underlain by a 209 m thick zone of transition into 1056.0 m of sheeted dykes and massive units (Fig. 2).

All of the rocks recovered from Hole 504B are altered to some degree and include various secondary minerals (Fig. 2). In the Hole 504B rocks, associations and chemistries of secondary minerals vary from place to place even at the thin section level, and low-variance assemblages of secondary minerals in the system of basaltic composition are scarce. This makes it difficult to define the equilibrium compositions and compatibilities of coexisting secondary minerals. Ishizuka (1989) made the assumption that the compositions of a group of minerals within veins or fractures 1–10 mm thick, or one vug a few mm in diameter, or of minerals replacing a primary phase, together approximate the equilibrium compositions. He then established that the equilibrium mineral assemblages of laumontite + prehnite + epidote + chlorite and prehnite + actinolite + epidote + chlorite occur in the altered doleritic basalt at 1354.0 mbsf and 1482.8 mbsf, respectively. The former is diagnostic of a high-temperature in the zeolite facies, whereas the latter is indicative of the prehnite-actinolite facies (Liou *et al.*, 1987). Partial or high-variance mineral assemblages of the low-temperature zeolite facies, greenschist facies and amphibolite facies are common in the upper, middle and lower part of Hole 504B, respectively (Fig. 2). It is,

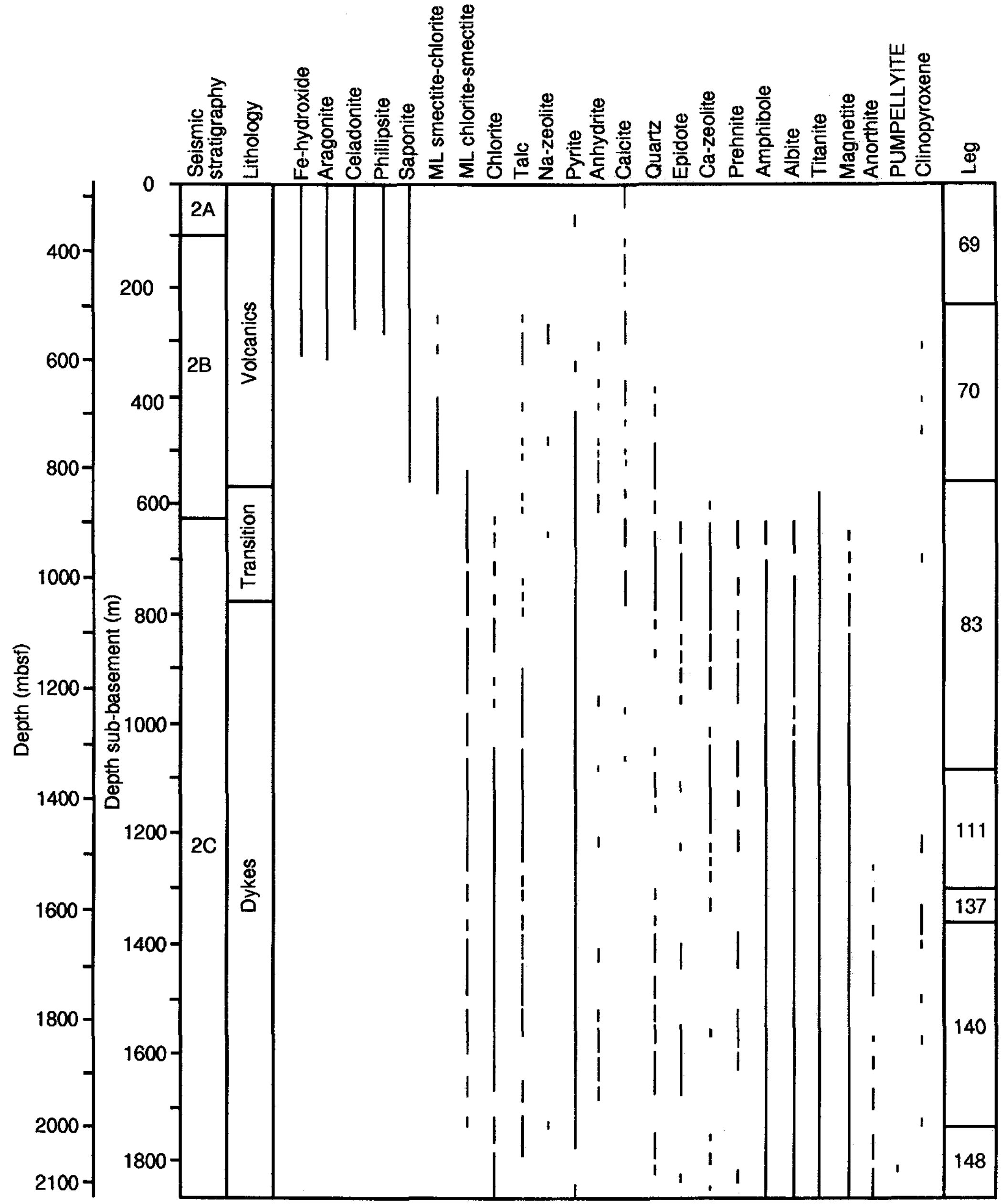


FIG. 2. Seismic stratigraphy, lithology, and secondary mineralogy with depth in Hole 504B (from Shipboard Scientific Party, 1993; Vanko *et al.*, 1996). Abbreviations: mbsf = m below sea floor; ML = mixed-layer; Na-zeolite includes analcime, natrolite, stilbite and epistilbite; Ca-zeolite includes laumontite, heulandite and scolecite. Magnetite, anorthite and clinopyroxene are not igneous but secondary minerals; their detailed petrographies have been described by Alt *et al.* (1985), Laverne (1987), Ishizuka (1989), and by Vanko and Laverne (1998).

therefore, likely that the grade (temperature) of alteration in Hole 504B increased primarily downwards from seafloor weathering through zeolite facies and prehnite-actinolite facies to greenschist facies, into the amphibolite facies. In addition, the overprinting of late-stage and lower-grade alteration especially by the development of vein and/or fracture filling minerals is also ubiquitous (e.g. Shipboard Scientific Party, 1993).

Sample description

Pumpellyite was found in only one thin section from the sample (No. 148-504B-249R-1, Piece 27, 87–89 cm) recovered during ODP Leg 148. The sample comes from the sheeted dyke complex at 2072.1 mbsf, and belongs to Lithologic Unit 290. Thirty three other samples from 2000.4–2111.0 mbsf have also been examined in the present study, but they contain no pumpellyite.

The sample is moderately altered, but it lacks evidence of strong shear stress or widespread penetrative deformation. Petrographically, it is a moderately aphyric and fine-grained doleritic basalt with subophitic texture, containing <1% olivine and 2% plagioclase phenocrysts that are set in a groundmass composed of olivine, plagioclase, clinopyroxene and minor magnetite. There is no sign of vesiculation, although irregular mm-sized vugs are present.

Bulk rock compositions of Lithologic Unit 290 rocks have been analysed by XRF (Shipboard Scientific Party, 1993; Bach *et al.*, 1996) and ICP-MS (Bach *et al.*, 1996), and are listed in Table 1. The rocks of Lithologic Unit 290 are moderately evolved MORBs (MgO = 8.37–9.15 wt.%, Fe_2O_3* = 8.77–10.7, Ni = 86–144 ppm, Cr = 265–332 ppm), and depleted in incompatible elements (e.g. Zr: 43–53 ppm, Nb: <1 ppm). Chondrite-normalized La/Sm and Nb/Zr ratios are considerably lower than average N-MORB, also suggesting a depleted mantle source (Bach *et al.*, 1996). This geochemical signature is characteristic of the Hole 504B sheeted dyke complex as well as overlying pillow lavas (Shipboard Scientific Party, 1993; Bach *et al.*, 1996).

TABLE 1. Bulk rock analyses of Lithologic Unit 290 from Hole 504B, Leg 148

Core	249R-1[a]	249R-1[b]	249R-1[b]
Interval (cm)	92-98	4-8	71-76
Piece #	28	2	24
Depth (mbsf)	2072.12	2071.24	2071.91
% alteration	44	30	30
Major elements (wt.%)			
SiO_2	49.22	49.6	50.3
TiO_2	0.74	1.03	0.84
Al_2O_3	15.70	14.8	16.4
Fe_2O_3*	8.77	10.7	9.35
MnO	0.14	0.19	0.15
MgO	9.15	8.37	8.8
CaO	13.21	13.0	13.4
Na_2O	1.70	2.11	1.85
K_2O	<0.14	<0.01	<0.01
P_2O_5	0.04	0.07	0.06
Total	98.81	99.9	101.1
Trace elements (ppm)			
S	170	210	100
Sc	34	45	41
Cr	265	267	332
Ni	144	86	121
Cu	23	77	38
Zn	29	53	38
Ga	15	15	15
Rb	3	0.23	0.17
Sr	55	66	59
Y	20	27	22
Zr	46	53	43
Nb	<1	0.59	0.51

Fe_2O_3* means total iron as Fe_2O_3.
Data[a] are from Shipboard Scientific Party (1993) and data[b] from Bach *et al.* (1996).

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, or vugs). In the pumpellyite-bearing thin section, ~40% of the primary phases were replaced by such secondary minerals as pumpellyite, prehnite, amphibole, chlorite, anorthite, albite, calcite, titanite and chalcopyrite. Of particular interest is the unique occurrence of secondary anorthite that is also recorded from samples of the deep sheeted dykes in Hole 504B (Fig. 2), which has recently been described in detail by Vanko and Laverne (1998).

Among the secondary minerals, pumpellyite is restricted to the partial replacement of one primary plagioclase phenocryst in the thin section, and occurs as fine-grained crystal aggregates (Fig. 3). Under the microscope, it exhibits colourless to bluish-green pleochroism with abnormal blue interference colour. Associated minerals include primary magnetite

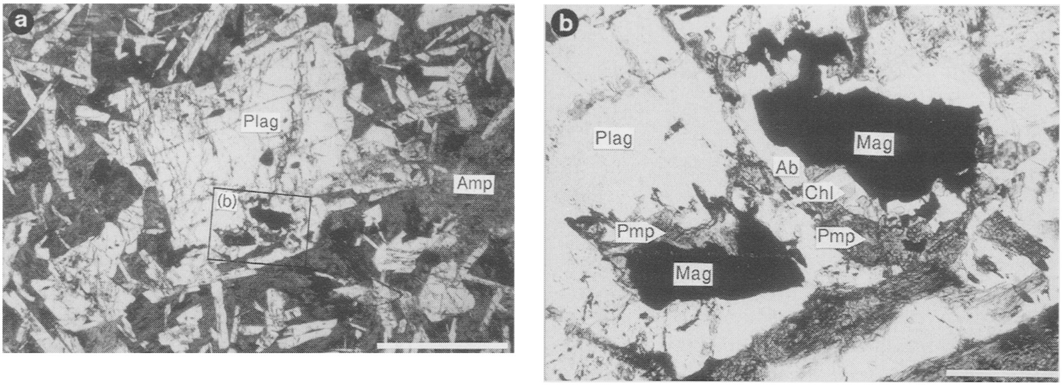


FIG. 3. Photomicrographs of Hole 504B pumpellyites replacing primary plagioclase phenocryst (*a*) and its close-up view (*b*) in plane polarized light. The scale bars are 1.0 mm in (*a*) and 0.2 mm in (*b*). Abbreviations: Ab = albite, Amp = amphibole, Chl = chlorite, Mag = primary magnetite, Plag = primary plagioclase phenocryst., Pmp = pumpellyite.

and secondary albite, chlorite and chalcopyrite, of which primary magnetite is sometimes surrounded by chalcopyrite, and albite grains characteristically develop between pumpellyite and primary plagioclase, separating these two minerals.

Other portions of the same thin section are pumpellyite-free, and include such secondary minerals as prehnite, amphibole, chlorite, anorthite, albite, calcite and titanite. These secondary minerals also occur as replacements of primary phases. Olivine is totally altered to chlorite and/or calcite, plagioclase is partially replaced by albite and/or anorthite, and occasionally prehnite, and clinopyroxene is partially replaced by amphibole and/or chlorite. Furthermore, interstitial space is occupied by amphibole, chlorite and titanite, and veins and fractures are filled by amphibole and/or prehnite.

Compositions of secondary minerals

Representative microprobe analyses of secondary minerals were determined using a JEOL JXA-8600MX at Kochi University and are listed in Table 2.

Pumpellyite

Assuming that the cation sites are completely filled, i.e. without vacancies, Coombs *et al.* (1976) proposed the following general chemical formula for pumpellyite: $W_4X_2Y_4Z_6O_{(20+x')}OH_{(8-x')}$, where W = Ca, Mn; X = (Mg, Fe^{2+}, Mn)$_{(2-x')}$(Fe^{3+},Al)$_{x'}$; Y = Al, Fe^{3+}; Z = Si, Al. In reliable pumpellyite analyses reviewed by Passaglia and Gottardi (1973), the value of (Mg, Fe^{2+}, Mn) for the X-site ranges from 0.71 to 1.55, and the value of (Fe^{3+}, Al) for the same site ranges from 1.29 to 0.45 per formula unit. Yoshiasa and Matsumoto (1985) arrived at the same chemical formula by using crystal structure refinement techniques, and showed that the electric charge is compensated by the amounts of hydrogen atoms. This means that the ferric and ferrous ions cannot be determined by the recalculation of total FeO using the stoichiometry of the crystal structure. This chemical formula was used in the present study, and the atomic formulae were calculated on the basis of 16 cations (Table 2).

There are slight variations in the Hole 504B pumpellyite composition. In particular, Fe* (total iron as Fe^{2+}) varies antithetically relative to Al and Mg (Fig. 4). The MgO content is restricted to a range of 2.1 to 2.6 wt.%. These relationships suggest that the substitution of Fe^{3+} by Al is dominant, accompanied by minor substitution of Fe^{2+} by Mg. The TiO_2 and MnO contents are typically <0.1 and 0.15 wt.%, respectively, and the alkalis are negligible.

Compared with other pumpellyites from the ocean floor and ophiolites on the Al-Fe*-Mg diagram (Fig. 5), the Hole 504B pumpellyites have similar compositions to those from the prehnite-pumpellyite facies rocks of the Vema fracture zone, Mid-Atlantic Ridge (Mevel, 1981), the Sumis Rift and Ohmachi Seamount, western Pacific (Yuasa *et al.*, 1993), and from the epidote

TABLE 2. Representative mineral analyses of the sample, 148-504B-249R-1, piece 27, 87–89 cm

	Pumpellyite-bearing portion					Pumpellyite-free portions				
	Pmp	Pmp	Pmp	Chl	Plag	Prh	Prh	Amp	Amp	Chl
SiO_2	37.96	37.50	37.13	26.25	45.44	43.50	43.61	51.09	51.53	27.36
TiO_2	0.06	0.04	0.10	0.05	0.01	0.09	0.07	0.23	0.14	0.02
Al_2O_3	25.45	21.77	19.53	18.35	33.54	20.91	23.51	3.23	3.54	18.88
Fe_2O_3*					0.56	4.54	1.96			
FeO*	5.22	8.12	12.08	24.55				13.85	11.74	17.05
MnO	0.11	0.13	0.11	0.02	0.03	0.04	0.01	0.25	0.22	0.14
MgO	2.57	2.53	2.24	17.45	0.02	2.49	1.72	15.10	16.32	22.37
CaO	22.51	22.79	22.80	0.14	18.20	25.13	25.37	12.03	12.43	0.16
Na_2O	0.02	0.02	0.02	0.04	1.29	0.07	0.03	0.52	0.54	0.10
K_2O	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	93.91	92.92	94.02	87.03	99.27	96.75	96.28	96.30	96.46	86.08
	TC=16	TC=16	TC=16	O=28	O=8	O=11	O=11	O=23	O=23	O=28
Si	6.05	6.10	6.05	5.572	2.114	2.992	2.982	7.536	7.516	5.628
Ti	0.01	0.01	0.01	0.008	0.000	0.005	0.004	0.026	0.015	0.003
Al	4.78	4.18	3.75	4.592	1.840	1.695	1.895	0.562	0.609	4.578
Fe^{3+}*					0.020	0.234	0.101			
Fe^{2+}*	0.70	1.11	1.65	4.358				1.709	1.432	2.933
Mn	0.01	0.02	0.02	0.036	0.001	0.002	0.001	0.032	0.027	0.024
Mg	0.61	0.60	0.54	5.520	0.014	0.255	0.175	3.320	3.547	6.858
Ca	3.83	3.96	3.98	0.032	0.908	1.852	1.859	1.901	1.943	0.035
Na	0.01	0.01	0.00	0.017	0.116	0.009	0.004	0.149	0.153	0.040
K	0.00	0.01	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	16.00	16.00	16.00	20.137	5.013	7.044	7.021	15.235	15.242	20.099

Fe_2O_3* (Fe^{3+}*) and FeO* (Fe^{2+}*) mean total iron as Fe_2O_3 (Fe^{3+}) and FeO (Fe^{2+}), respectively.
Abbreviations: Pmp = pumpellyite, Chl = chlorite, Plag = primary plagioclase, Prh = prehnite, Amp = amphibole mineral, TC = total cation.

and pumpellyite zone rocks of the Del Puerto ophiolite (Ewarts and Schiffman, 1983), but are apparently more aluminous than those from the zeolite facies matabasites of the East Taiwan ophiolite (Liou, 1979) and Horokanai ophiolite (Ishizuka, 1991), and from the zeolite zone rocks of the Del Puerto ophiolite (Ewarts and Schiffman, 1983). Of these, the pumpellyites from the Vema Fracture zone, Ohmachi Seamount and Horokanai ophiolite have been described as replacements of primary plagioclases, similar to the Hole 504B pumpellyites. It is very important to compare the pumpellyite compositions, because in low-grade metamorphic rocks pumpellyite compositions have been known to depend strongly upon compositions of precursor phases which pumpellyite replaces, and that the pumpellyites replacing plagioclase are the most aluminous (AlDahan, 1989; Ishizuka, 1991). The Hole 504B pumpellyites are apparently poor in Mg compared with those from the Garrett fracture zone of the East Pacific Rise (Bideau *et al.*, 1991). The Garrett pumpellyites develop in monomineralic veinlets of rodingite and gabbronorite.

Prehnite

Compositionally, besides the major oxides (SiO_2, Al_2O_3, and CaO), the analysed prehnites contain a considerable amount of Fe_2O_3*, ranging from 1.7 to 4.5 wt.%. The MgO content is also up to 2.5 wt.%. The increase in Fe_2O_3* and MgO seems to be accompanied by the decrease in Al_2O_3.

Amphibole

On the diagram by Leake *et al.* (1997), the analysed amphibole minerals plot in the field of actinolite to magnesiohornblende. The Na_2O

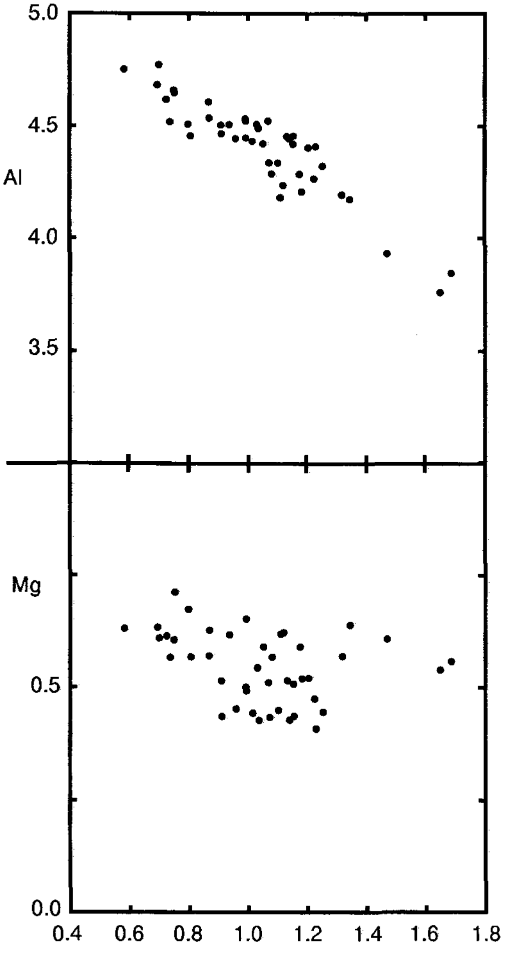


FIG. 4. Compositions of Hole 504B pumpellyites plotted on Fe*-Al and Fe*-Mg diagrams.

content ranges from 0.35 to 0.97 wt.%, and the K_2O content is negligible. A preliminary analysis of chlorine indicates up to 0.15 wt.% Cl, suggesting the presence of a saline hydrothermal fluid of sea-water origin (Vanko, 1986).

Chlorite

Chlorite occurs in both the pumpellyite-bearing and pumpellyite-free portions, commonly taking the form of fine-grained aggregates. Although the SiO_2 content of the chlorite is rather constant, its Fe*/(Fe* + Mg) ratio is apparently higher in the pumpellyite-bearing portion (0.37–0.44) than in the pumpellyite-free portions (0.28–0.35). This may reflect the occurrence of primary magnetite closely associated with the pumpellyite-bearing portion. On the diagram of Hey (1954) the chlorites plot as dominant pycnochlorite and less common ripidolite.

Discussion and conclusions

The mineral associations observed in the sample show some variations from place to place even within a single thin section. The pumpellyite is restricted to the partial replacement of one primary plagioclase phenocryst (An_{85-88}), associated with chlorite, albite, chalcopyrite and primary magnetite. Other portions in the same thin section, such as in a vein, partial replacements of primary phases, and interstitial spaces, are pumpellyite-free and contain prehnite, amphibole, chlorite, anorthite, albite, titanite and Fe-Ti oxides. Furthermore, the chlorite compositions from the pumpellyite-bearing portion are rich in Fe and poor in Mg, compared with those from the pumpellyite-free portions. Such variations of mineral associations and chemistries can be attributed to local differences in effective bulk compositions, and chemical equilibrium is not attained even in a thin section, as seems to be common in low-grade metamorphic rocks (e.g. Liou *et al.*, 1987). Therefore, to analyse the equilibrium phase relations, we must attend to the pumpellyite-bearing and pumpellyite-free associations separately.

The textural relationship indicates that alteration of primary plagioclase and associated primary magnetite have led to the formation of pumpellyite accompanied by albite and chlorite. This requires a H_2O-rich fluid phase that also supplied S and Cu to produce chalcopyrite. Hydrothermal circulation of hot seawater may have been the main process controlling the behaviour of such a fluid phase, a conclusion supported by the considerable amount of chlorine in the analysed amphiboles.

The *P-T* conditions for this hydrothermal alteration are estimated as follows: (1) the sample was drilled from the depth of 2072.1 mbsf, and the water depth of Hole 504B is 3460 m, suggesting the pressure to be ~1 kbar; (2) there is no zeolite mineral in the thin section, indicating that the temperature has exceeded the zeolite facies, which is consistent with pumpellyite compositions being more aluminous than

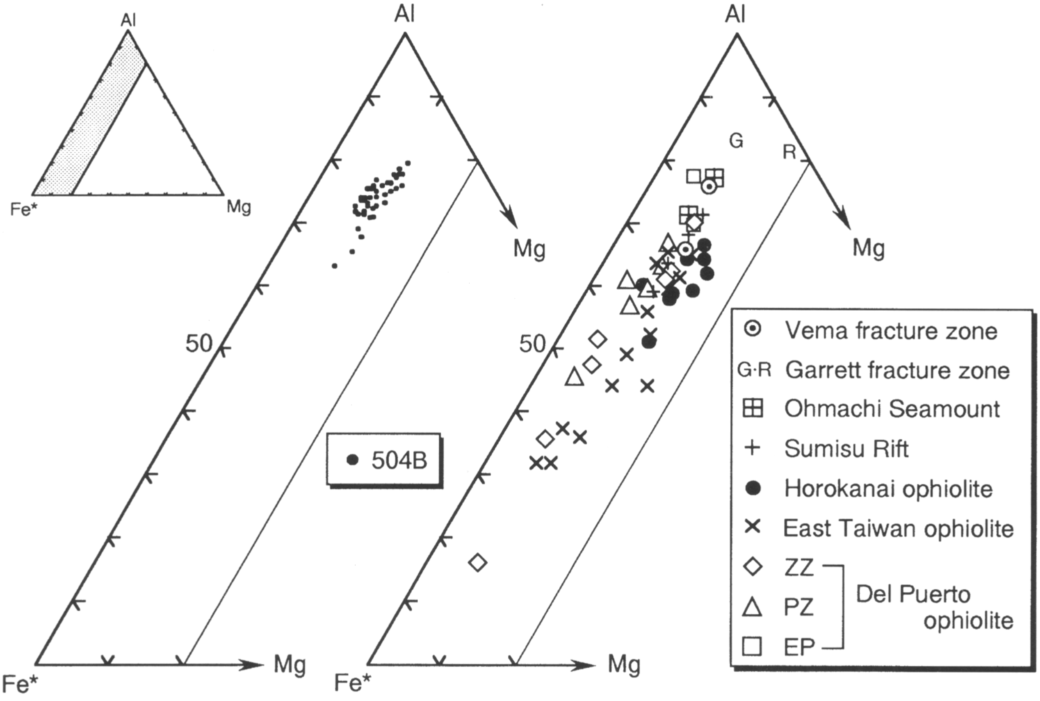


FIG. 5. Fe*-Al-Mg diagram showing pumpellyite compositions from Hole 504B (present study), the Vema fracture zone of the Mid-Atlantic Ridge (Mevel, 1981), the Garrett fracture zone of the East Pacific Rise (Bideau *et al.*, 1991), the Sumisu Rift and Ohmachi Seamount of western Pacific (Yuasa *et al.*, 1993), the East Taiwan ophiolite (Liou, 1979), the Horokanai ophiolite (Ishizuka, 1991), and the Del Puerto ophiolite (Ewarts and Schiffman, 1983). Of these, the data of the Vema fracture zone, Ohmachi Seamount and Horokanai ophiolite are from pumpellyites occurring as replacements of primary plagioclases. G and R indicate Garrett pumpellyites from gabbronorite and rodingite, respectively. Abbreviations: ZZ = zeolite zone, PZ = pumpellyite zone, EZ = epidote zone.

those of the zeolite facies (Fig. 5) because higher temperatures favour aluminous pumpellyites (Ishizuka, 1991); (3) the upper stability limit of the zeolite facies for low-pressure conditions is defined by the reaction laumontite + prehnite = epidote + quartz + H_2O, which is independent of pressure and is located at temperatures of ~230°C in the Al-end-member system and ~160°C in the Fe^{3+}-rich system such as the $Fe^{3+}/(Fe^{3+} + Al)$ ratio of epidote being 0.3 (Liou *et al.*, 1987); and (4) Fe- and Mg-pumpellyite are stable at temperatures up to a maximum of 240°C (Schiffman and Liou, 1980) and 350°C (Schiffman and Liou, 1983), respectively, at pressure of 2 kbar. It is, therefore, likely that the pumpellyite described here may have been formed during hydrothermal alteration at pressure of about 1 kbar and temperatures of 160–350°C. Further quantitative estimate of *P-T* conditions is quite difficult because of the absence of a low-variance pumpellyite-bearing assemblage in the sample.

The mineral associations observed in the pumpellyite-free portions such as prehnite + amphibole + chlorite could be partial assemblages of the prehnite-actinolite facies (Liou *et al.*, 1987; Ishizuka, 1989). This mineral facies can be seen to occupy a large *P-T* field transitional from the zeolite or prehnite-pumpellyite to greenschist facies at low pressures (Liou *et al.*, 1987). The fact that the equilibrium low-variance mineral assemblage diagnostic of the prehnite-actinolite facies, prehnite + actinolite + epidote + chlorite, has been described in the drilled sample from 1482.8 mbsf of Hole 504B (Ishizuka, 1989) suggests the existence of this mineral facies in Hole 504B. It follows that the temperature was less than the greenschist facies conditions

(350–400°C at PH_2O = P_{load} inferred from Fig. 3.8 of Liou *et al.*, 1987), which is also consistent with the formative conditions of pumpellyite estimated above.

In conclusion, the present study reveals that, if appropriate bulk compositions are available, pumpellyite can be formed during oceanic ridge hydrothermal alteration. If this is the case, it is expected that more extensive dredging and drilling of oceanic crust may show pumpellyite to be more widespread than previously thought.

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References

AlDahan, A.A. (1989) The paragenesis of pumpellyite in granitic rocks from the Siljan area, central Sweden. *Neues. Jahrb. Mineral. Mh.*, 367–83.

Alt, J.C., Laverne, C. and Muehlenbachs, K. (1985) Alteration of the upper oceanic crust: mineralogy and processes in deep sea drilling project Hole 504B, Leg 83. In *Init. Repts. DSDP*, **83**, (R.N. Anderson, J. Honnorez, K. Becker, *et al.*, eds). U.S. Govt. Printing Office, Washington, pp. 217–62.

Bach W., Erzinger, J., Alt, J.C. and Teagle, D.A.H. (1996) Chemistry of the lower sheeted dike complex, Hole 504B (Leg 148): influence of magmatic differentiation and hydrothermal alteration. In *Proc. ODP, Sci. Results*, **148**, (J.C. Alt, H. Kinoshita, L.B. Stokking and P.J. Michael, eds). Ocean Drilling Program, College Station, Texas, pp. 39–55.

Bideau, D., Hebert, R., Hekinian, R. and Cannet, M. (1991) Metamorphism of deep-seated rocks from the Garrett ultrafast transform (East Pacific Rise near 13°25'S). *J. Geophys. Res.*, **96**, 10079–99.

Coombs, D.S., Nakamura, Y. and Vuagnat, M. (1976) Pumpellyite-actinolite facies schists of the Taveyanne Formation near Loèche, Valais, Switzerland. *J. Petrol.*, **17**, 440–71.

Ewarts, R.C. and Schiffman, P. (1983) Submarine hydrothermal metamorphism of the Del Puerto ophiolite, California. *Amer. J. Sci.*, **283**, 289–340.

Hey, M.H. (1954) A new review of the chlorites. *Mineral. Mag.*, **30**, 277–97.

Hobart, M.A., Langseth, M.G. and Anderson, R.N. (1985) A geothermal and geophysical survey on the south flank of the Costa Rica Rift: Site 504 and 505. In *Init. Repts. DSDP*, **83**, (R.N. Anderson, J. Honnorez, K. Becker *et al.*, eds). U.S. Govt. Printing Office, Washington, pp. 379–404.

Ishizuka, H. (1989) Mineral paragenesis of altered basalts from Hole 504B, ODP Leg 111. In *Proc. ODP, Sci. Results*, **111**, (K. Becker, H. Sakai *et al.*, eds), Ocean Drilling Program, College Station, Texas, pp. 61–76.

Ishizuka, H. (1991) Pumpellyite from zeolite facies metabasites of the Horokanai ophiolite in the Kamuikotan zone, Hokkaido, Japan. *Contrib. Mineral. Petrol.*, **107**, 1–7.

Laverne, C. (1987) Unusual occurrences of aegirine-augite, fassaite and melanite in oceanic basalts (DSDP Hole 504B). *Lithos*, **20**, 135–51.

Leake, B.E., Woolley, A.R., Arps, C.E.S. and others (1997) Nomenclature of amphiboles: report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. *Mineral. Mag.*, **61**, 295–321.

Liou, J.G. (1979) Zeolite facies metamorphism of basaltic rocks from the East Taiwan Ophiolite. *Amer. Mineral.*, **64**, 1–14.

Liou, J.G., Maruyama, S. and Cho, M. (1987) Very low-grade metamorphism of volcaniclastic rocks-mineral assemblages and mineral facies. In *Very Low-Grade Metamorphism*, (M. Frey, ed.). Blackie and Son, New York, pp. 59–113.

Melson, W.G., Thompson, G. and van Andel, T.H. (1968) Volcanism and metamorphism in the Mid-Atlantic Ridge, 22°N latitude. *J. Geophys. Res.*, **73**, 5925–41.

Mevel, C. (1981) Occurrence of pumpellyite in hydrothermally altered basalts from the Vema fracture zone (Mid-Atlantic Ridge). *Contrib. Mineral. Petrol.*, **76**, 386–93.

Passaglia, E. and Gottardi, G. (1973) Crystal chemistry and nomenclature of pumpellyite and julgoldites. *Canad. Mineral.*, **12**, 219–23.

Schiffman, P. and Liou, J.G. (1980) Synthesis and stability relations of Mg-Al pumpellyite, $Ca_4Al_5MgSi_6O_{21}(OH)_7$. *J. Petrol.*, **21**, 441–74.

Schiffman, P. and Liou, J.G. (1983) Synthesis of Fe-pumpellyite and its stability relations with epidote. *J. metam. Geol.*, **1**, 91–101.

Shipboard Scientific Party (1993) Site 504. In *Proc. ODP, Init. Rept*, **148**, (J.C. Alt, H. Kinoshita, L.B. Stokking and P.J. Michael, eds). Ocean Drilling Program, College Station, Texas, pp. 27–121.

Vanko, D.A. (1986) High-chlorine amphiboles from oceanic rocks: product of highly-saline hydrothermal fluids? *Amer. Mineral.*, **71**, 51–9.

Vanko, D.A. and Laverne, C. (1998) Hydrothermal anorthitization of plagioclase within the magmatic/hydrothermal transition at mid-ocean ridges: examples from deep sheeted dikes (Hole 504B, Costa Rica Rife) and a sheeted dike root zone (Oman ophiolite). *Earth Planet. Sci. Lett.*, **162**, 27–43.

Vanko, D.A., Laverne, C., Tartarotti, P. and Alt, J.C. (1996) Chemistry and origin of secondary minerals from the deep sheeted dikes cored during Leg 148 (Hole 504B). In *Proc. ODP, Sci. Results*, **148**, (J.C. Alt, H. Kinoshita, L.B. Stokking and P.J. Michael, eds). Ocean Drilling Program, College Station, Texas, pp. 71–86.

Yoshiasa, A. and Matsumoto, T. (1985) Crystal structure refinement and crystal chemistry of pumpellyite. *Amer. Mineral.*, **70**, 1011–19.

Yuasa, M., Watanabe, T., Kuwajima, T., Hirama, T. and Fujioka, K. (1993) Prehnite-pumpellyite facies metamorphism in oceanic arc basement from Site 791 in the Sumisu Rift, western Pacific. In *Proc. ODP, Sci. Results*, **126**, (B. Taylor, K. Fujioka *et al.*, eds). Ocean Drilling Program, College Station, Texas, pp. 185–93.

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