

33. OCCURRENCE OF MELANITE AND AEGIRINE-AUGITE IN DEEP SEA DRILLING PROJECT HOLE 504B¹

Christine Laverne, Laboratoire de Géologie, B.P. 5, 97490 Ste Clotilde (Réunion), France

ABSTRACT

In three veins from the lower part of Deep Sea Drilling Project Hole 504B, 298 meters below the top of basement, primary augite is replaced by aegirine-augite. This transformation occurs only in subophitic basalts, at the contact with veins which always include a dark-olive, Mg-rich clay mineral.

Talc occurs in one of these veins; it can be regarded either as a vein constituent or as a product of augite alteration.

Melanite (Ca,Fe,Ti-rich garnet) appears in only one of these three veins, where a Ca-carbonate is associated with a Mg-rich clay mineral. The occurrence of melanite in Hole 504B could be due to the conjunction of particular conditions: (1) basalt with a subophitic texture, (2) presence of hydrothermal fluids carrying Ca, Fe, Si, Ti, Al, Mg, and Na, (3) rather high temperatures. Possibly the melanite and aegirine-augite formed by deuteric alteration.

INTRODUCTION

The aim of this paper is to describe very unusual secondary parageneses in basalts from the lower part of Hole 504B, drilled on 5.9-m.y.-old crust on the south flank of the Costa Rica Rift. Melanite (Ti-rich andradite) and secondary aegirine-augite were found in veins 298 meters below the top of basement, and deeper, where temperatures rather higher than those which cause classical low-temperature alteration were probably reached (Honnorez et al., this volume).

ANALYTICAL METHODS

In altered basalts, secondary minerals—particularly clay minerals—are sometimes plucked out during thin-section preparation, preventing complete observation with an optical microscope.

Electron-microprobe analyses were carried out at the Centre Oceanologique de Bretagne (Brest, France). During the analyses, the accelerating voltage was kept at 15.0 kV. The electron-beam incidence has a take-off angle of about 42°, and the limit of detection is about 500 ppm. The precision of the method used is about 1% of the absolute value of the measured concentration.

SAMPLE DESCRIPTION

In oceanic basalts, titanomagnetite is the first magmatic mineral to be altered. Then, olivine and possibly plagioclase are replaced by secondary products, but pyroxene is the magmatic mineral regarded as more resistant to alteration. Usually, pyroxene is completely fresh in basalts altered at low temperatures.

From the lower part of Hole 504B, three samples contain partly altered pyroxene crystals. These rocks are subophitic basalts, and the altered pyroxene crystals are always in direct contact with a secondary-mineral vein.

Each of these samples deserves description, because the vein mineral paragenesis of each is particular.

Sample 504B-40-1, 37–39 cm (depth below sediment/basement interface 298 m)

A 0.2- to 0.5-mm thick vein crosses the basalt. It is mainly composed of a calcium carbonate mineral (Table 1) occurring as anhedral or euhedral crystals, and a dark-olive-green clay mineral without obvious crystal boundaries. I could not determine whether this carbonate is calcite or aragonite or a mixture of both. The clay mineral (Table 2) is MgO-rich ($\approx 24\%$), richer in Al_2O_3 ($\approx 9\%$) and poorer in SiO_2 ($\approx 41\%$) than most of the analyzed smectites from Hole 504B (Honnorez et al., this volume). Because of its particular chemistry, this clay mineral may not be pure smectite, but a regular mixed-layer clay mineral instead. This point will be addressed in a future study.

Almost all of the pyroxene crystals are partly altered all along the vein. Those portions of the pyroxene crystals adjacent to the vein wall are replaced by a bright-

Table 1. Microprobe analyses of Ca-carbonate in the vein of Sample 504B-40-1, 37–39 cm.

Component	Analysis	
	1	2
SiO ₂	—	—
Al ₂ O ₃	—	—
FeO*	—	—
MnO	—	—
MgO	—	—
CaO	63.80	64.00
Na ₂ O	0.06	—
K ₂ O	—	—
TiO ₂	—	0.01
NiO	—	—
Cr ₂ O ₃	0.10	0.03
P ₂ O ₅	0.79	0.67
Total	64.74	64.71

*Total iron as FeO.

¹ Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office).

Table 2. Microprobe analyses of talc and clay minerals forming veins in samples containing aegirine-augite.

Component	Analysis										
	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	60.18	62.47	61.51	61.34	60.53	60.35	58.37	44.89	40.64	45.25	45.38
Al ₂ O ₃	1.23	0.96	0.92	0.84	1.17	1.07	2.29	9.14	9.42	6.49	6.69
FeO*	1.52	0.34	0.83	0.93	1.60	1.26	2.23	4.56	11.55	13.36	12.91
MnO	—	0.01	—	0.06	—	—	—	—	0.23	—	0.07
MgO	30.27	30.82	29.85	30.24	29.73	30.16	29.45	22.89	24.21	20.07	20.03
CaO	0.11	0.06	0.07	0.09	0.18	0.08	0.16	1.03	0.99	1.39	1.83
Na ₂ O	0.22	0.13	0.19	0.20	0.24	0.19	0.34	0.32	0.28	0.03	0.14
K ₂ O	0.01	—	—	0.08	0.05	0.03	0.14	1.06	0.28	0.17	0.20
TiO ₂	0.02	0.04	0.08	0.04	0.26	0.24	0.07	0.03	0.01	0.02	0.12
NiO	—	—	—	0.03	—	0.04	—	—	—	—	—
Cr ₂ O ₃	0.02	0.03	0.05	—	0.11	0.02	0.04	0.01	—	0.01	—
P ₂ O ₅	—	—	—	0.03	—	0.04	—	n.d.	—	—	—
Total	93.56	94.87	93.49	93.85	93.89	93.43	93.08	83.93	87.61	86.78	87.36
Si	7.82	7.94	7.95	7.91	7.85	7.84	7.66	6.76	6.14	6.87	6.85
Al	0.19	0.14	0.14	0.13	0.18	0.16	0.35	1.62	1.67	1.16	1.19
Fe*	0.17	0.04	0.09	0.10	0.17	0.14	0.24	0.57	1.45	1.69	1.62
Mn	—	—	—	0.01	—	—	—	—	0.03	—	0.01
Mg	5.86	5.84	5.75	5.82	5.75	5.84	5.80	5.14	5.49	4.57	4.53
Ca	0.02	0.01	0.01	0.01	0.03	0.01	0.02	0.17	0.16	0.23	0.30
Na	0.06	0.03	0.05	0.05	0.06	0.05	0.09	0.09	0.08	0.01	0.04
K	—	—	—	0.01	0.01	—	0.02	0.20	0.05	0.03	0.04
Ti	—	—	0.01	—	0.03	0.02	0.01	—	—	—	0.01
Ni	—	—	—	—	—	—	—	—	—	—	—
Cr	—	—	—	—	—	—	—	—	—	—	—
P	—	—	—	—	—	—	—	—	—	—	—

Notes: 1 to 7: 504B-52-3, 103-107 cm, No. 1034; 1 to 4: talc layer close to aegirine-augite; 5 and 6: talc fibers in vein; 7: colorless, slightly Fe-rich talc needle, growing from pyroxene?; 8 and 9: 504B-40-1, 37-39 cm, No. 507; 8: dark-olive clay mineral in vein; 9: dark-olive clay mineral between two pyroxene crystals, at the vein wall; 10 and 11: 504B-58-1, 9-13 cm, No. 1189; dark-olive clay mineral in vein.
Number of ions on the basis of 22 oxygens.

*Total iron as FeO.

green material with weak birefringence (0.009–0.010) and a somewhat granular or fibrous appearance. This green zone generally is thin (<0.005 mm). Numerous tiny, colorless or pale-green needles (maximum length 0.4 mm; maximum width 0.005 mm) have crystallized perpendicular to the green zone, or all around the pyroxene crystals (Fig. 1).

In order to determine and visualize the chemical differences between fresh and altered pyroxene, both electron-microprobe analyses and X-ray scanning microphotographs were used (Table 3, Fig. 2). Compared to the fresh pyroxene, the green altered zone is richer in Na, Ti, and Fe, and poorer in Al and Mg. (Fig. 3). Ca, Si, and H₂O contents have been affected only slightly by this transformation; thus, the green material has the composition of a Ti-rich aegirine-augite.

It was difficult to determine the chemical composition of the colorless needles because of their very small size. Nevertheless, it does not seem to be drastically different from the aegirine-augite replacing magmatic augite in this sample. Because of the relationship between augite, aegirine-augite, and the colorless needles, one can assume that they are also a replacement product of augite.

A confused area occurs in some parts of the vein zone, where one observes small green crystals isolated in a dark-olive clay-mineral matrix. Some of the green crystals are fragments of aegirine-augite, whereas some others, much rarer, are euhedral crystals of unidentified minerals.

The most striking feature of this vein-paragenesis is the presence of a Ti,Ca,Fe-rich garnet, which occurs only in this sample. Four crystals were found in three thin-sections. The garnet crystals often are adjacent to the vein walls; one of them grew partly around a feld-

spar microphenocryst, two others are in contact with pyroxene crystals, and the fourth one apparently is not adjacent to the vein wall.

The garnet crystals have hexagonal cross-sections (Figs. 1, 4, and 5) and are 0.2 mm in diameter; they display a dark-brownish-green color without crossed polars, with a very slight apparent zoning. A very particular twin is observed (Fig. 6), which is similar to what Lacroix (1892) called the "pyreneitic" twin type.

Chemical analyses (Table 4) indicate that the garnet belongs to the andradite group. Its high TiO₂ content (0.71–6.42%) is characteristic of melanite (1–5% TiO₂) or shorlomite (TiO₂ > 5%) (Deer et al., 1963). The TiO₂ content varies within the same crystal; this important point appears clearly on X-ray pictures showing zoning of Ti and Al. In Figures 5 and 7, one can observe in a melanite crystal the concentric disposition of thin Ti-rich and Al-poor layers, parallel to the crystal edges; Mg, Si, Ca, and Fe do not contribute to the zoning. Thus, the variations of the chemical composition of the solution during the crystallization of melanite are probably responsible for this zoning. In any case, Ti and Al seem to have been "mobile" during garnet formation. It is clear in Ti and Al distribution pictures that the growth of this crystal was disturbed by a Mg-rich and Al-poor mineral, which could not be identified (Fig. 5).

Sample 504B-52-3, 103–107 cm (depth 395 m)

The studied vein (width <1 mm) is made up of a dark-olive-green clay mineral, and much more rarely by a slightly flexible, colorless, highly birefringent mineral. The clay mineral could not be analyzed because it was poorly polished. The colorless mineral is talc (Table 2), which either contains small amounts of iron or is mixed with a Fe-rich smectite. No carbonate was observed.

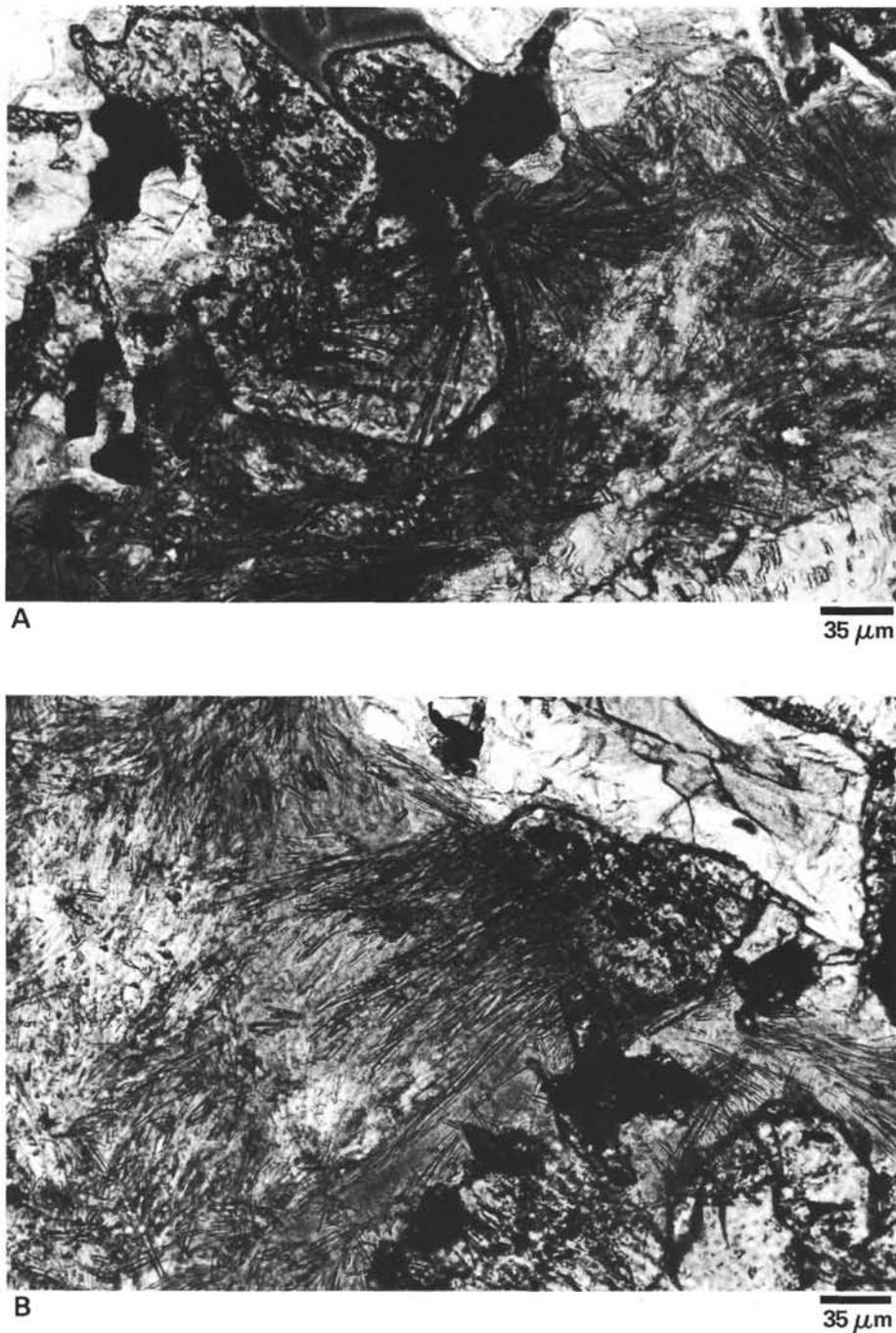


Figure 1. A. Slightly zoned melanite crystal growing near (and from?) aegirine-augite in the salband of a mineral vein composed of Ca-carbonate and dark-olive clay. 504B-40-1, 37-39 cm. Plane-polarized light. B. Primary augite partly replaced by aegirine-augite and an unidentified opaque mineral, in the salband of a mineral vein composed of Ca-carbonate and dark-olive clay mineral. Numerous needles, with composition locally similar to that of aegirine-augite, have crystallized perpendicular to the augite-crystal edge. 504B-40-1, 37-39 cm. Plane-polarized light.

Rare colorless needles occur, the chemistry of which is similar to that of talc (Table 2). As in Sample 504B-40-1, 37-39 cm, the edges of the pyroxene crystals which are in contact with the vein are altered to aegirine-augite (Table 3), which is more Na- and Fe-rich than fresh magmatic augite. There appears to be no significant variation of Ti content in these minerals, unlike the Core 40

sample previously described. All along this vein, a very particular sequence is observed (Fig. 8): from a fresh pyroxene to the center of the vein, one can successively observe (1) a somewhat fibrous aegirine-augite and tiny patches of a granular, orange, probably Fe-rich material; (2) talc, as a thin (0.02 mm) layer; (3) a dark-olive clay mineral. Moreover, some of the aegirine-augites have

Table 3. Augite and aegirine-augite microprobe analyses, Hole 504B.

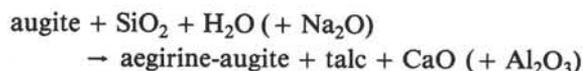
Component	Analysis																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO ₂	52.73	50.99	50.72	50.53	53.33	51.44	54.21	54.04	52.27	52.35	53.38	52.97	51.69	52.14	51.82	52.37	50.88	51.84
TiO ₂	0.41	0.81	2.85	2.97	0.38	0.09	0.67	0.86	—	0.27	0.93	0.75	—	0.01	0.70	0.13	0.39	0.56
Al ₂ O ₃	2.66	2.60	0.78	0.73	2.43	0.45	0.65	0.82	0.43	3.58	0.98	0.73	0.56	0.43	3.45	0.45	0.28	0.47
FeO*	5.69	15.02	16.35	15.27	6.78	20.56	11.20	14.67	15.76	4.36	15.82	14.64	19.74	20.71	7.13	14.58	21.54	17.32
MnO	0.07	0.36	0.05	—	0.21	0.39	0.23	0.23	0.18	0.12	0.18	0.16	0.25	0.15	0.10	0.16	0.13	0.28
MgO	18.34	13.88	7.33	7.64	18.71	5.64	11.81	9.34	8.68	17.56	8.14	10.19	6.09	6.36	16.70	9.66	6.01	7.94
CaO	18.34	16.63	18.73	18.93	17.05	17.09	16.16	12.70	20.93	21.63	13.35	15.23	16.56	15.23	19.28	19.94	19.33	19.33
Na ₂ O	0.20	0.29	3.21	3.08	0.16	3.07	4.08	6.41	0.51	0.22	7.17	6.39	4.52	5.45	0.23	1.97	1.56	1.87
K ₂ O	—	—	—	—	—	—	—	—	—	—	0.03	—	—	0.01	—	—	—	—
NiO	—	—	—	0.11	—	—	—	0.02	—	0.08	—	0.11	—	0.02	0.07	—	—	—
Cr ₂ O ₃	0.48	0.04	—	0.02	0.25	0.05	0.06	—	—	1.07	0.09	0.04	0.13	—	0.08	—	—	—
P ₂ O ₅	0.98	0.29	0.47	0.26	0.28	0.47	0.26	0.22	0.44	n.a.	n.a.	.a	n.a.	n.a.	0.26	0.27	0.18	0.26
Total	99.21	100.90	100.90	99.54	99.58	99.23	99.35	99.30	99.28	101.16	100.45	101.10	99.56	100.54	99.76	99.55	100.30	99.97
Si	1.930	1.911	1.953	1.959	1.944	2.030	2.037	2.059	2.017	1.892	2.036	2.005	2.034	2.036	1.906	2.011	2.002	2.008
Ti	0.011	0.023	0.083	0.087	0.010	0.003	0.019	0.025	—	0.007	0.027	0.021	—	—	0.019	0.004	0.012	0.016
Al	0.115	0.115	0.035	0.033	0.105	0.021	0.029	0.037	0.019	0.153	0.044	0.032	0.026	0.020	0.150	0.020	0.013	0.021
Fe	0.174	0.471	0.527	0.695	0.207	0.678	0.352	0.467	0.508	0.132	0.505	0.463	0.650	0.676	0.219	0.468	0.709	0.561
Mn	0.002	0.012	0.002	—	0.006	0.013	0.007	0.008	0.006	0.004	0.006	0.005	0.008	0.005	0.003	0.005	0.004	0.009
Mg	1.000	0.775	0.421	0.442	1.016	0.332	0.662	0.530	0.499	0.946	0.478	0.575	0.357	0.370	0.916	0.553	0.352	0.458
Ca	0.719	0.668	0.773	0.786	0.666	0.722	0.651	0.518	0.865	0.837	0.546	0.618	0.698	0.637	0.760	0.820	0.815	0.802
Na	0.014	0.021	0.240	0.232	0.012	0.235	0.297	0.473	0.038	0.015	0.530	0.469	0.345	0.412	0.016	0.147	0.119	0.140
K	—	—	—	—	—	0.001	—	—	—	—	0.001	—	—	—	0.003	—	—	—
Ni	—	—	—	n.c.	—	—	0.005	—	0.002	—	0.004	—	—	—	0.002	—	—	—
Cr	0.014	0.001	—	n.c.	0.007	0.001	0.002	—	—	0.031	0.003	0.001	0.004	—	n.c.	—	—	—
P	0.009	0.009	0.015	0.009	0.009	0.016	0.008	0.007	0.014	n.a.	n.a.	n.a.	n.a.	n.a.	0.008	0.009	0.006	0.009
Total	3.9884	4.005	4.049	4.043	3.982	4.050	4.064	4.123	3.971	4.0164	4.179	4.190	4.123	4.160	3.997	4.037	4.032	4.024
WO	37.93	34.68	44.92	45.62	35.12	41.39	38.92	34.03	46.06	43.65	35.58	37.17	40.76	37.74	40.11	44.54	43.44	44.04
EN	52.76	40.28	24.46	25.65	53.62	19.00	39.59	34.80	26.57	49.29	31.15	34.61	20.84	21.92	48.34	30.04	18.76	25.15
FS	9.31	25.05	30.62	28.73	11.26	39.62	21.49	31.17	27.37	7.06	33.27	28.22	38.40	40.34	11.56	25.42	37.79	30.81

Notes: 1 to 4: 504B-40-1, 37-39 cm, No. 507; 1: unaltered augite; 2: slightly altered pyroxene; 3 and 4: Ti-rich aegirine-augite replacing material of analysis 2; 5 to 14: 504B-52-3, 103-107 cm, No. 1034; 5: unaltered augite (avg. of 2 analyses); 6 to 9: aegirine augite replacing material of analysis 5; 10: unaltered augite; 11 to 14: aegirine-augite replacing material of analysis 10; 15 to 18: 504B-58-1, 9-13 cm, No. 1189; 15: unaltered augite; 16 to 18: aegirine-augite replacing material of analysis 15.

a granular appearance; an analyzed granular aegirine-augite is even more Fe-rich (up to 20.7%) and MgO-poor (6.1%) than fibrous aegirine-augite (Table 3, analysis 13).

The element distribution is shown by X-ray scanning microphotographs (Fig. 9). Notice that the dark-olive clay mineral is Mg-rich, whereas the Mg-rich smectite that we usually found in Hole 504B (Honnorez et al., this volume) is colorless or very pale green. This suggests that the dark-olive clay mineral is not pure smectite, but possibly a mixed-layer clay mineral or a mixture of clay minerals.

Talc occurs only in this sample. Because of its location in the vein salband, it can be regarded either as a vein constituent or as a product of augite alteration. Fibrous talc associated with the dark-olive clay mineral clearly is a vein component. The role of the thin talc layer located close to aegirine-augite is more uncertain; in Figure 10, the average chemical compositions of unaltered augite, secondary aegirine-augite, and talc from this sample are compared. Unaltered augite has a composition intermediate with respect to NaO, FeO*, and MgO. Thus, it seems that, when augite is altered, Fe, and Na are concentrated in aegirine-augite, and Mg in talc. A hypothetical reaction is suggested:



One may assume that, during this reaction, part of the Mg necessary to form talc comes from the alteration of augite, but that another part may come from another source, which is also responsible for talc and the Mg-rich, dark-olive clay mineral of the vein.

Sample 504B-58-1, 9-13 cm (depth 445 m)

The vein crossing this sample is composed of a dark-olive-green clay mineral (white to orange between crossed polars), and pyrite. The clay mineral is MgO-rich (20%) and Al₂O₃-rich (6.5%) (Table 2). It probably is not pure smectite, but a mixed-layer clay mineral or a mixture of clay minerals. This important point will be determined by X-ray diffraction in a future study.

Most of the pyroxene crystals are fresh, even near the vein. Only a few crystals show an aegirine-augite layer (Table 3), similar to those described above.

Table 5 summarizes the modes of occurrence of aegirine-augite in Hole 504B.

DISCUSSION ON THE OCCURRENCE OF AEGIRINE-AUGITE, MELANITE, AND TALC

Aegirine-Augite

Fortey et al. (1978) mentioned the occurrence of aegirine-augite of possible authigenic origin in Devonian sediments of Scotland. The aegirine-augite composition is remarkably pure and very close to that of a unique occurrence of authigenic aegirine in the lacustrine Green River Formation of Wyoming, U.S.A. (Milton et al., 1960; Hay, 1966); these authors suggest that the aegirine-augite "formed in hypersaline conditions in which sodium may have been derived from contemporaneous alkaline volcanism within the Orcadian basin". However, the compositions of both this authigenic aegirine-augite and that of igneous or metamorphic origin are different (Table 6). On the other hand, the Hole 504B aegirine-augite composition is very similar to that of some of the igneous and metamorphic aegirine-augite.

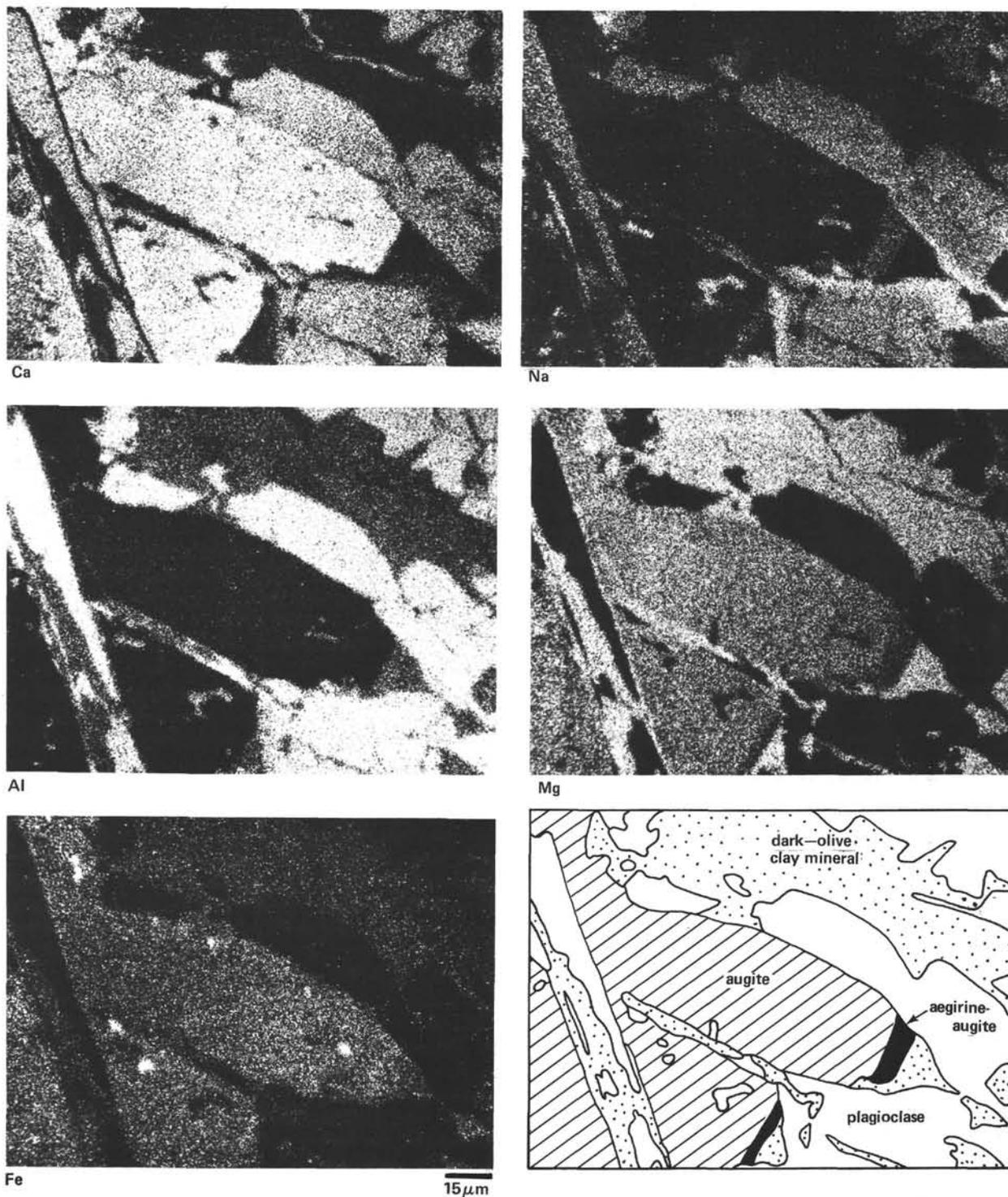


Figure 2. Scanning electron photomicrograph of two augite crystals partly replaced by aegirine-augite. The Mg-rich material is the clay mineral composing the vein.

The formation of aegirine-augite from augite adjacent to natrolite veins in analcite-olivine dolerite has been described by Suzuki (1938).

I suggest that several conditions favored formation of secondary aegirine-augite from magmatic augite of Hole 504B basalts:

- 1) The veins are found in *subophitic* basalts. This texture may allow a stability of chemical conditions in the veins for a long time, hence the transformation of augite.
- 2) The presence of a dark-olive, Mg-rich clay mineral in the veins suggests very local chemical and thermal conditions.

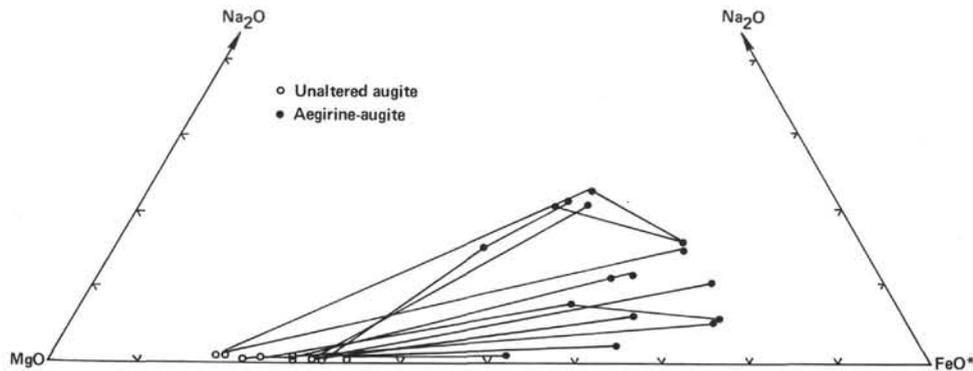


Figure 3. Na_2O - MgO - FeO^* diagram showing chemical variations resulting from alteration of primary augite to secondary aegirine-augite in Hole 504B. The lines link unaltered and altered augite of the same pyroxene phenocryst.

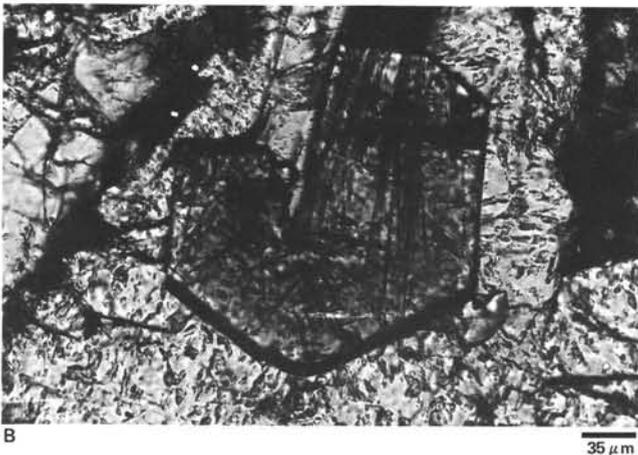


Figure 4. A. Melanite crystal in the salband of a carbonate vein. The vein is in the lower half of the picture. The white lath forming the upper left boundary of the melanite crystal is plagioclase. 504B-40-1, 37-39 cm. Plane-polarized light. B. Detail of Figure 4A. One can observe a faint zoning in melanite. Notice the occurrence of fine needles in melanite. Plane-polarized light.

3) Higher temperatures occurred than those prevailing during low-temperature alteration, because aegirine-augite was observed only in the lowest part of the Hole 504B (and below 298 m), where measured temperatures range from 59 to 125°C (Becker et al., this volume).

The small number of samples from Hole 504B where aegirine-augite occurs does not allow me to conclude much more about the conditions of formation of this mineral.

Melanite

According to Deer et al. (1963), melanite and shorlomite occur either in alkaline igneous rocks such as nepheline syenite, ijolite, phonolite, and nephelinite, or in skarns.

A chemical analogy exists between the mineral parageneses associated with melanite in Hole 504B and in skarns. Various elements were necessary to form melanite in the vein of Sample 504B-40-1, 37-39 cm:

1) Ca, Fe, and Si are also responsible for Ca-carbonate and dark-olive-clay-mineral formation in the vein. Recall that primary minerals in the host basalt are less altered than those of adjacent samples from similar depths; plagioclase is fresh and olivine is only *partly* replaced by smectite and carbonates (Honnorez et al., this volume). Thus, I think that these elements mainly come from circulating hydrothermal fluids, not from the alteration of the nearby magmatic minerals.

2) Ti also may come from hydrothermal fluids, because aegirine-augite is richer in Ti than unaltered augite, and because the Ti content of the other primary transparent minerals (olivine, plagioclase) is not affected by alteration.

Thus, it seems that the metasomatic hydrothermal addition of Ca, Si, Fe, and Ti allowed the formation of melanite.

Hydrogarnets thought to be hydrothermal in origin have been found in sediments at DSDP Site 251 (Kempe et al., 1974; Cook et al., 1974), but no garnet has been found in the basaltic basement cores until now.

In their extensive review of low temperature metasomatic garnets in marine sediments, Easton et al. (1977)

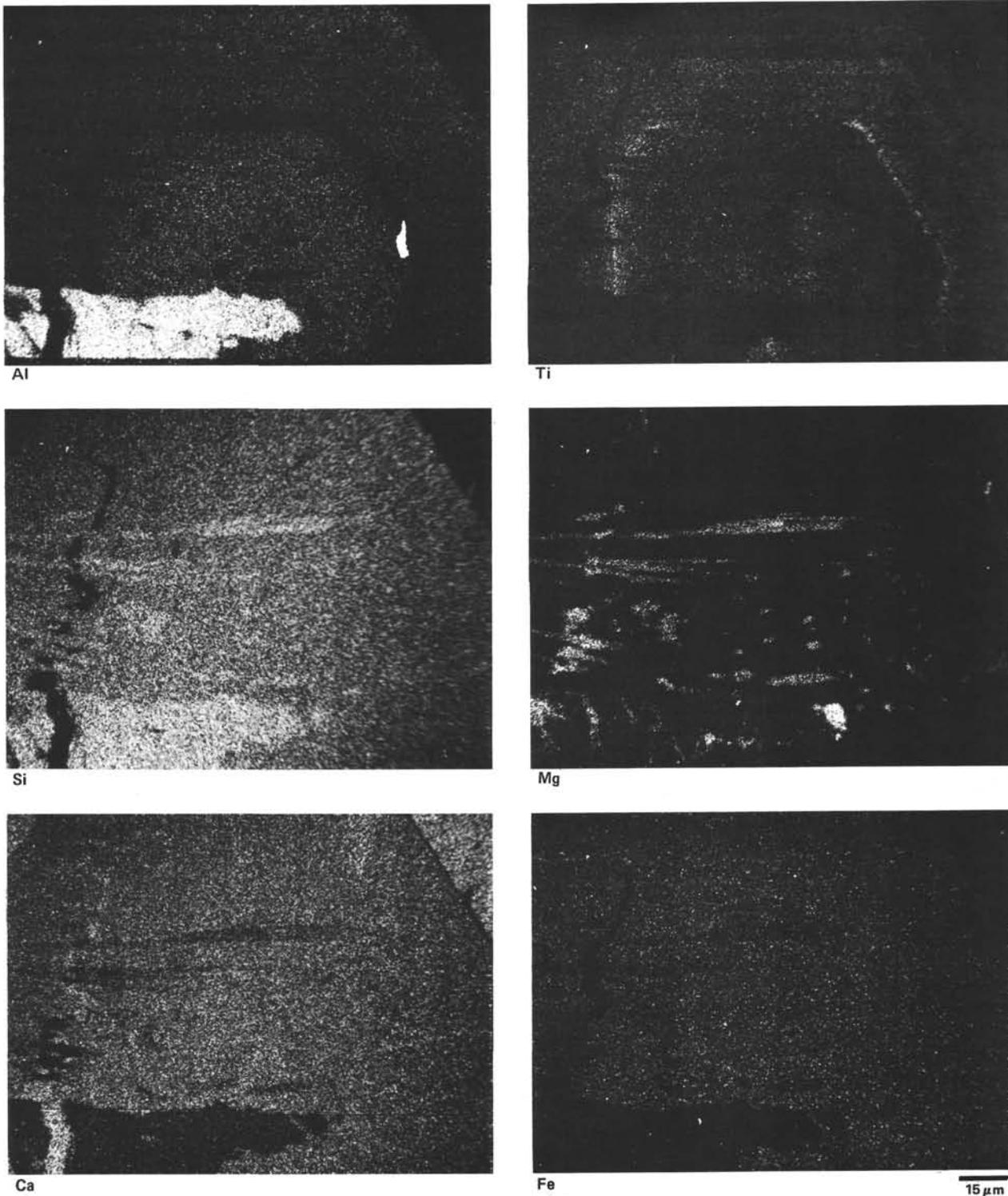


Figure 5. Scanning electron photomicrograph of a melanite crystal in Sample 504B-40-1, 37-39 cm. Same crystal as in Figure 4. The Al, Si-rich area is a plagioclase lath. In melanite, Si, Mg, Ca, and Fe contents are constant, whereas Al and Ti contents vary in compositional zones. Si- and Mg-rich, colorless needles can be seen in melanite. Two edges of the crystal occur in the upper left and right corners.

ruled out the possibility that hydrogrossular found in chalk overlying the basement at DSDP Site 251 had an "origin by baking or low-grade contact metamorphism", because (1) "the basalt is basement and not an intrusive sill"; (2) "if the growth of such garnets was caused by thermal metamorphism, their occurrence

would be widespread". They propose an origin by primary precipitation from circulating sea water hydrothermal solutions, at about 170°C.

However, the garnets from Site 251 are very different from those from Hole 504B; they are hydrogarnets without Ti.

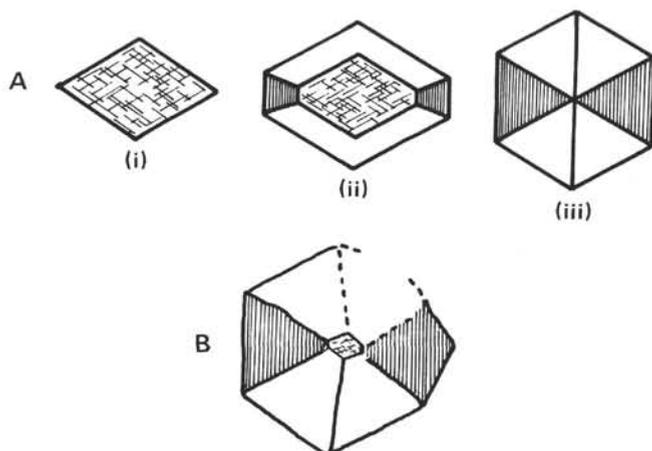


Figure 6. Pyreneite twins in melanite-type garnets. A. Sections (110) in the garnet of Framont, France (pyreneite-type): (i) at the surface of the crystal; (ii) half way to the center; (iii) through the center (after Lacroix, 1892). B. Section (110) in a melanite crystal from Hole 504B; this section is intermediate in position between (ii) and (iii) of the Framont garnet.

Table 4. Microprobe analyses of andradite and melanite from Hole 504B, Sample 504B-40-1, 37-39 cm, No. 507.

Component	Analysis							
	1	2	3	4	5	6	7	8
SiO ₂	35.89	36.06	33.75	35.39	35.92	36.44	35.91	37.41
Al ₂ O ₃	4.49	7.72	2.76	3.73	4.87	6.30	5.80	7.37
Fe ₂ O ₃	21.61	19.73	20.86	24.57	22.98	21.47	21.78	20.63
TiO ₂	3.41	0.71	6.42	1.73	2.30	1.37	1.38	0.78
MgO	0.08	0.07	0.18	0.08	0.02	0.08	0.06	0.05
FeO	1.07	1.64	2.80	0.20	0.06	1.37	1.38	1.02
MnO	0.27	0.28	0.36	0.46	0.22	0.05	0.08	0.08
Na ₂ O	0.05	—	0.22	0.05	—	0.06	0.01	0.02
CaO	32.42	32.84	31.58	33.49	33.33	33.22	33.62	33.03
K ₂ O	—	—	—	—	—	0.03	0.02	—
NiO	—	—	—	0.02	—	0.06	—	—
Cr ₂ O ₃	—	0.01	—	—	—	—	—	—
P ₂ O ₅	0.45	0.60	0.49	0.57	0.56	n.d.	n.d.	0.57
Total	99.74	99.66	99.41	100.29	100.26	100.32	100.28	100.96
Si	5.890	5.875	5.641	5.835	5.863	5.943	5.885	5.994
Al	0.868	1.483	0.544	0.724	0.937	1.211	1.121	1.392
Fe ³⁺	2.668	2.418	2.624	3.049	2.840	2.635	2.686	2.487
Ti	0.421	0.088	0.807	0.214	0.282	0.152	0.197	0.094
Mg	0.020	0.016	0.046	0.019	0.005	0.019	0.016	0.012
Fe ²⁺	0.147	0.223	0.391	0.028	0.008	0.187	0.190	0.137
Mn	0.038	0.039	0.051	0.065	—	0.007	0.011	0.011
Na	0.015	—	0.071	0.015	—	0.018	0.005	0.006
Ca	5.701	5.733	5.655	5.917	5.828	5.806	5.903	5.670
K	—	—	—	—	—	0.006	0.004	—
Ni	—	—	—	0.031	—	0.008	—	—
Cr	—	0.007	—	—	—	—	—	—
P	0.063	0.083	0.069	0.080	0.077	n.d.	n.d.	0.077
Total	15.831	15.960	15.898	15.949	15.840	15.992	16.017	15.880
Al	2.61	3.74	6.91	—	0.14	3.15	3.15	2.35
Py	0.35	0.28	0.81	0.32	0.09	0.32	0.26	0.21
Sp	0.67	0.66	0.89	—	0.52	0.13	0.19	0.19
Gr	18.87	33.11	9.00	17.61	19.66	27.41	26.29	32.19
Ad	77.51	62.20	82.39	82.07	79.60	68.99	70.11	65.06
Uv	—	0.02	—	—	—	—	—	—

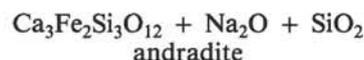
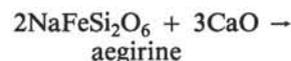
Hydrogrossular was found in oceanic rodingites (Honorez et al., 1975) as a replacement product of the original plagioclase. It is proposed that the rodingitization process has a metasomatic nature, characterized by enrichment in calcium and water contents, and depletion of the silica content of the final rodingite. The occurrence of hydrogrossular rather than grossular in the studied rodingites can be explained by their low potential in SiO₂.

The following hypothetical process can be proposed to explain the formation of melanite in Hole 504B. Af-

ter the emplacement of the subophitic basalt, circulating fluids carry large amounts of Si, Ca, Fe, Mg, Ti, Al, and Na along cracks. Because of the relative "impermeability" of the basalt texture, these hot fluids do not diffuse very much in the basalt, but move along the crack, where they cool probably slowly, allowing the formation of:

- 1) Large euhedral and anhedral Ca-carbonate crystals (Ca);
- 2) dark-olive, Mg-rich clay minerals (Mg, Si, Al);
- 3) aegirine-augite (Fe, Na, (Ti)); and
- 4) melanite crystals (Fe, Ca, Si, Ti, Al)

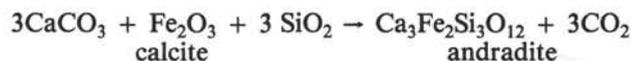
Deer et al. (1963) mention the possibility that andradite forms from aegirine according the reaction



Although two crystals of melanite from Hole 504B grew against aegirine-augite, I cannot affirm that melanite crystallized from aegirine-augite.

As described earlier, the garnet is zoned: Ti and Al are in concentric layers parallel to the crystal edges. This means that Ti and Al were "mobile" during the formation of melanite, but Ti has been considered immobile in alteration (Cann, 1970; Pearce and Cann, 1973; Pearce et al., 1975). This could mean that melanite did not form under alteration conditions, but possibly at higher temperatures, in contrast to hydrogarnets from Site 251.

It should be noted that such occurrences of andradite-type garnets have been described in ophiolitic pillow lavas. Juteau (1970) mentioned the presence of andradite in spilitic breccias from the submarine volcanic complex of Sayrun (Turkey). In this case, two conditions were necessary for andradite to form: a volcanic rock rich in calcite and iron oxides, and an important thermal metamorphism. The following reaction was proposed:



The circulation of hot fluids explains the formation of andradite (gain of SiO₂, and probably H₂O, O₂, etc., and loss of CO₂; Even et al., 1973).

Blanco-Sanchez (1978) thinks that this andradite, which is associated with analcite or hematite and calcite, could have formed in the zeolite facies or prehnite-pumpellyite facies; it occurs in veins and amygdaloids. The temperature of its formation probably did not exceed 400°C.

Thus, the mode of occurrence of andradite and melanite in Hole 504B seems not to differ very much from those described in ophiolitic pillow lavas.

According to Coombs et al. (1977), the temperature of formation of andradite found in metasediments (zeolite facies) from New Zealand is at least 300 to 400°C.

Experimental studies (Huckenholz and Hölz, 1977; Taylor and Liou, 1976) on the stability of andradite

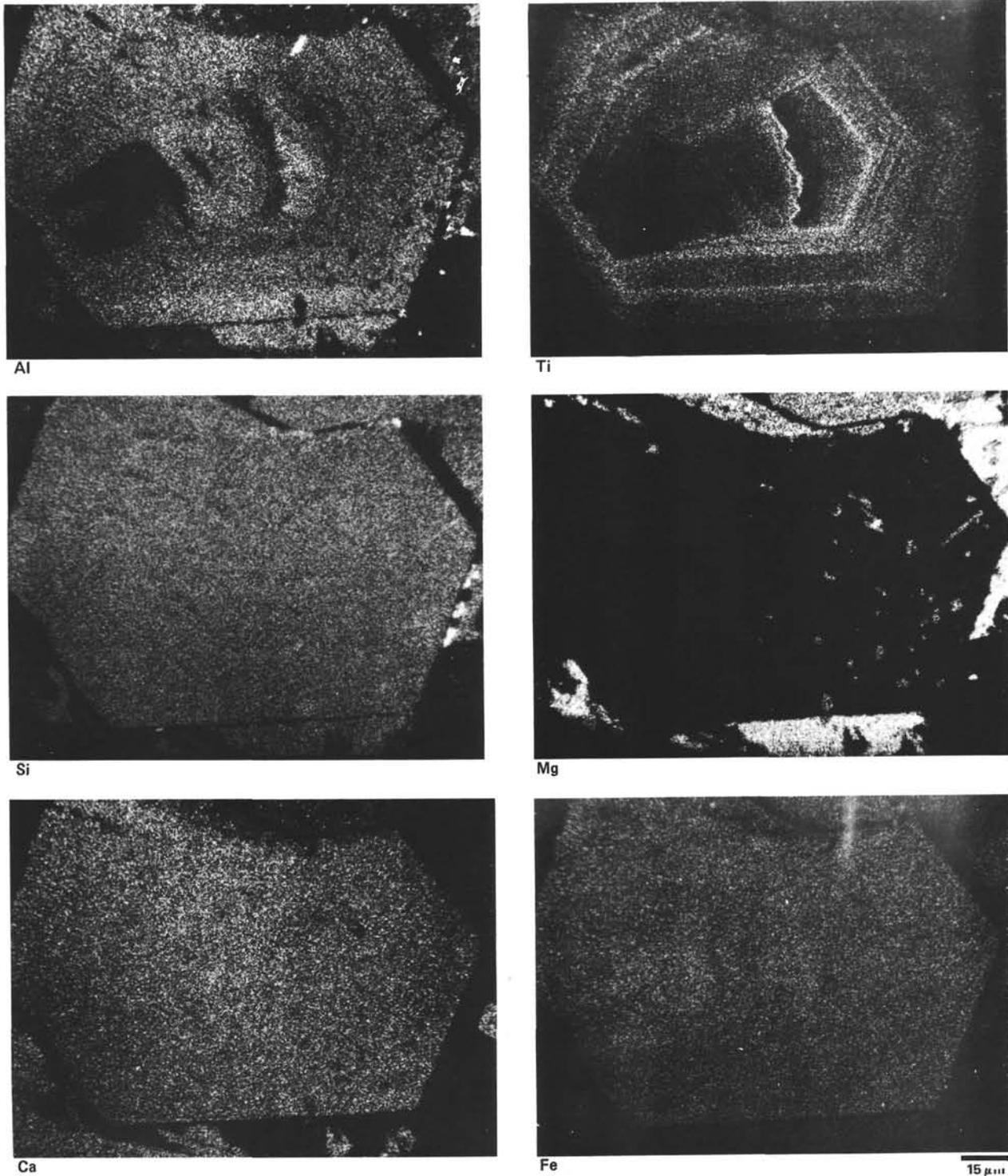


Figure 7. Scanning electron photomicrograph of a melanite crystal in Sample 504B-40-1, 37-39 cm. Al and Ti zonation can be observed clearly. The Mg-rich clay mineral composing the vein, and the Mg-rich needles, appear on the X-ray scan for Mg.

have shown the importance of oxygen fugacity to its formation.

Thus, one can ascribe the very unusual occurrence of melanite in Hole 504B to the conjunction of the following particular conditions:

1) Subophitic texture, allowing a long interaction between hydrothermal fluids and basalts;

- 2) The presence of hydrothermal fluids very rich in Ca, Fe, Si, Ti, Al, Mg, and Na;
- 3) Rather high temperatures.

Talc

Because of the distribution of talc in Hole 504B, and its very unusual location, one may assume that particu-

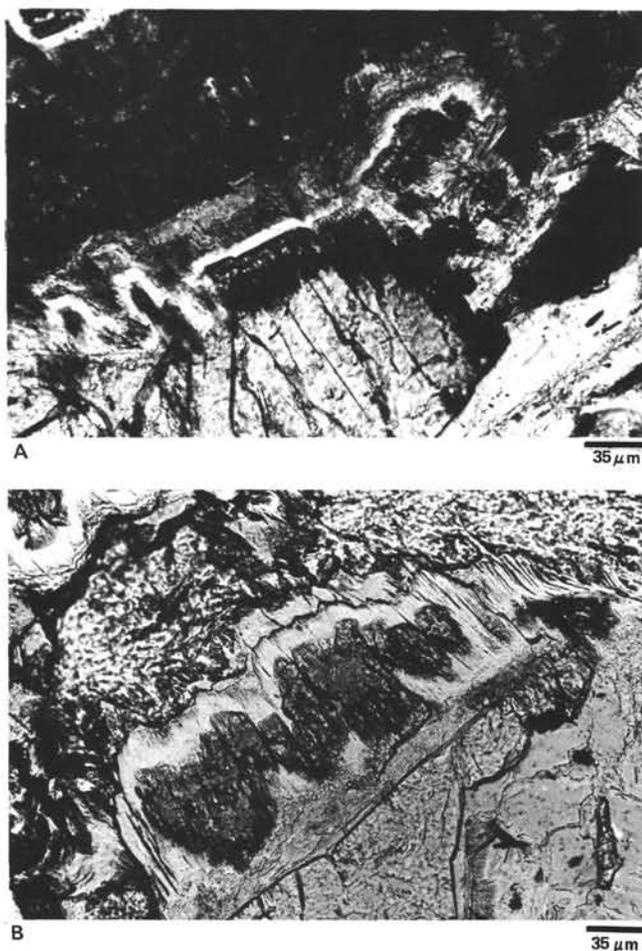


Figure 8. A. Augite at the contact with a vein composed of dark-olive clay mineral. From the bottom to the top of the picture, one can successively observe unaltered augite (light gray), aegirine-augite (dark gray to black), talc (white), dark-olive clay mineral (medium gray). In the upper left corner of the picture, one can observe talc + aegirine-augite of the opposite salband of the vein. 504B-52-3, 103–107 cm. Plane-polarized light. B. Same succession as in Figure 8A, but alteration is stronger. Aegirine-augite (dark gray) and talc (white) are well developed. The granular material in the vein is probably clay mineral plucked out during thin-section preparation. In the upper left corner of the picture, the other salband of the vein can be seen. 504B-52-3, 103–107 cm. Plane-polarized light.

lar chemical and thermodynamic conditions were necessary for talc to crystallize (an environment very rich in Mg and Si, and probably temperatures higher than in the upper part of Hole 504B; Honnorez et al., this volume).

Although melanite and aegirine-augite from Hole 504B seem to have an hydrothermal origin, one must not rule out the possibility that these minerals formed by deuteric alteration. At the end of the crystallization of the basalt, late-stage magmatic solutions and volatiles are able to move along cracks and to alter magmatic minerals. The location of the aegirine-augite and melanite at the vein salband supports this hypothesis.

SUMMARY AND CONCLUSIONS

In three veins from the lower part of Hole 504B, below 298 meters sub-basement depth, primary augite is

replaced by aegirine-augite with an increase of Na and Fe. This transformation occurs only at the contact with a vein, which is always composed of a dark-olive Mg-rich clay mineral.

Melanite (Ca,Fe,Ti-rich garnet) appears in a single sample where Ca-carbonate is associated with a Mg-rich clay mineral in the vein. Melanite formation seems to be due to hydrothermal fluids bringing Ca, Fe, Ti, Si, Mg, Al, and Na.

A future systematic study of the materials composing all the veins of the lower part of Hole 504B should allow determination of the frequency, distribution, and formation conditions of these unusual secondary minerals.

ACKNOWLEDGMENTS

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NOTE ADDED IN PROOF

Since I submitted this paper (May 1981) I have found two more veins that contain aegirine-augite in subophitic basalts. Fassaite occurs in one of them. These occurrences and X-ray data for the veins will be discussed and published at a later date.

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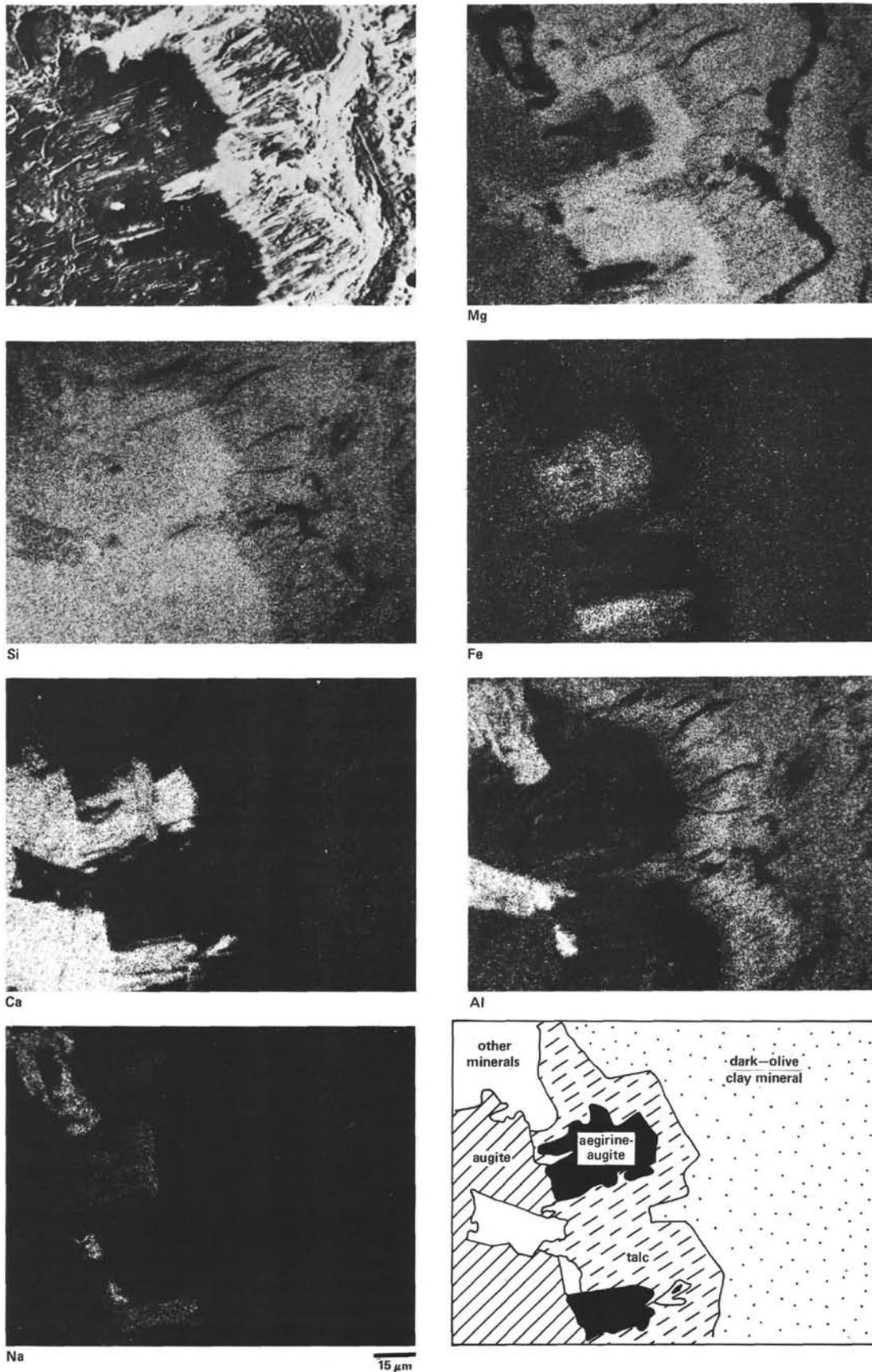


Figure 9. Scanning electron photomicrograph of the wall of a vein of Mg-rich clay mineral, with primary augite replaced by aegirine-augite and talc.

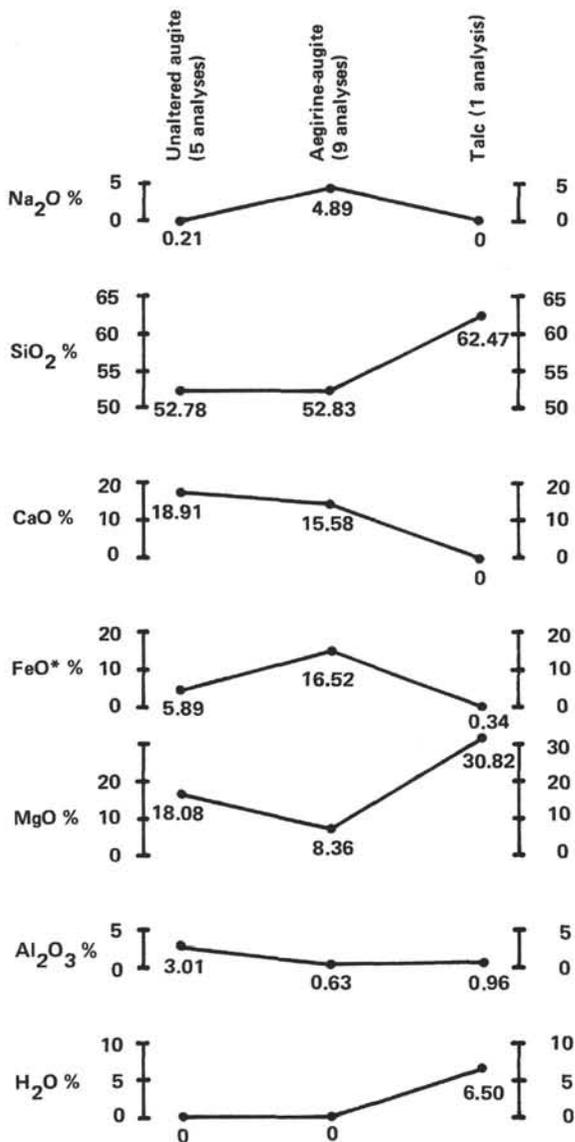


Figure 10. Comparison of the chemistry of augite, aegirine-augite, and talc in Sample 504B-52-3, 103-107 cm.

Table 5. Mode of occurrence of aegirine-augite in veins in Hole 504B altered basalts.

Sample (interval in cm)	Depth within Basement (m)	Mineral Paragenesis in the Veins
504B-40-1, 37-39	298	Ca-carbonate, dark-olive Mg-rich clay mineral, melanite, colorless needles with composition close to aegirine-augite
504B-52-3, 103-107	395	Talc, dark-olive Mg-rich clay mineral, colorless needles with composition close to talc
504B-58-1, 9-13	445	Dark-olive Mg-rich clay mineral, pyrite

Table 6. Comparison of microprobe analyses of aegirine-augite.

Component	Analyses					
	1	2	3	4	5	6
SiO ₂	52.31	51.35	51.40	51.68	51.54	50.5-54.2
TiO ₂	—	0.65	0.01	1.59	0.09	0.9
Al ₂ O ₃	—	2.88	1.67	1.28	0.93	0.3-1.0
Fe ₂ O ₃	34.32	25.43	4.32	19.10	8.21	—
FeO	—	3.70	8.10	5.17	6.86	11.2-21.5
MnO	0.01	0.18	0.27	0.45	0.30	0.4
MgO	0.06	0.58	10.60	4.29	9.10	7.3-13.9
CaO	—	3.29	21.98	9.56	19.04	12.7-20.9
Na ₂ O	13.96	11.65	1.47	7.25	3.43	0.3-7.2
K ₂ O	0.01	0.14	tr.	n.d.	0.02	—
V ₂ O ₃	0.02	0.02	—	—	—	n.d.
ZrO ₂	—	n.d.	—	—	—	n.d.
H ₂ O ⁺	—	0.24	0.29	0.05	0.34	n.d.
H ₂ O ⁻	—	0.09	—	0.05	0.06	n.d.
F	—	—	—	n.d.	0.01	n.d.
Total	100.69	100.20	100.11	100.47	99.99	—

Notes: Aegirine and aegirine-augite from (1) Devonian lacustrine beds of Caithness (Fortey et al., 1978); (2) the Assynt Complex (Sabine, 1950); (3) the Ben Loyal Complex (King, 1942); (4) Clen Lui (MacLachlan, 1951); (5) Narsaassuk (Boggild, 1953); (6) Hole 504B; tr. = trace; n.d. = not determined.