

18. PHYLLOSILICATE ALTERATION OF OLIVINE IN THE LOWER SHEETED DIKE COMPLEX, LEG 140, HOLE 504B¹

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ABSTRACT

Replacement minerals in olivine record the evolution of hydrothermal alteration between 1600 and 2000 mbsf in the sheeted dike complex in Hole 504B.

1. Talc (+ magnetite) rim on olivine represents the earliest alteration. Talc probably crystallized during initial cooling of the dikes.

2. The partial breakdown of talc to "deweylite," a chaotic mixture of serpentine and Al-free stevensite, was facilitated by further cooling and a somewhat increased fluid:rock interaction in the dikes.

3. The presence of chlorite veins and the replacement of unaltered olivine cores, talc, and deweylite and of other silicates by chlorite suggest fracturing of the rocks during cooling (shrinkage cracks) and local influx of seawater into the dikes.

4. Late amphibole veins and locally extensive amphibole alteration indicate increasing temperature and the development of new sets of fractures, possibly due to the injection of fresh magma.

Several generations of chlorite and amphibole veins are present in the dikes. Offset veins and the crack-seal texture within veins in the dikes suggest that the alteration cycle was probably repeated with the injection of each set of new dikes.

Presently measured temperatures (195°C) at 2000 m depth in Hole 504B indicate that deweylite, which was previously considered a low-temperature mineral, can form well above its previously estimated crystallization temperature of 50°C.

INTRODUCTION

Hole 504B was penetrated to a depth of 2000.4 mbsf during the drilling operations of Leg 140. This was the seventh leg (Deep Sea Drilling Project/Ocean Drilling Program) which drilled the 5.9 million-year-old oceanic crust in Hole 504B. Site 504 is located 200 km south of the Costa Rica Rift within the Panama Basin.

Hole 504B provides the only penetration into a sheeted dike complex of in-situ ocean crust. This reference section for the modern ocean crust comprises 274.5 m of sediment, 571.5 m of basalts, a 209-m transition zone, and 954.5 m of sheeted dikes (Dick, Erzinger, Stokking, et al., 1992). Our study documents mineralogical changes which occurred during the alteration of the sheeted dike complex (SDC) in the lowermost 350-m section of Hole 504B. Within this framework, our objectives are: (1) to determine the paragenetic sequence of alteration assemblages from replacement minerals in olivine and (2) to distinguish between amphibole generations, based on texture and mineral chemistry and determine their relationship to other replacement silicates in the SDC.

PREVIOUS WORK

Detailed mineralogical and alteration studies of rocks recovered in previous legs from Hole 504B have been published by numerous investigators (Honorez et al., 1983; Laverne, 1983; Becker, Sakai, et al., 1988; Alt et al., 1985, 1986, 1989). Alt et al. (1985) conducted a detailed study on chlorites and expandable clay mixtures based on

X-ray diffraction patterns, mineral chemistry and optical properties. They grouped chlorites and chlorite expandable clay mixtures into five distinct categories, concluding that chlorites with high proportions of expandable clays are generally more Si-rich and Fe-poor than pure chlorites, and found that the smectite component in mixed layer chlorites decreased with depth due to increasing temperature and decreasing permeability of the dikes.

The mineralogy and texture of altered rocks recovered during Leg 140 have been described in detail by the Shipboard Scientific Party (Dick, Erzinger, Stokking, et al., 1992). On the basis of petrography, combined with some major and trace element geochemistry, it was concluded that (1) alteration intensity within the dikes decreases with depth in the lowermost part of the SDC (presence of fresh olivine), (2) the coexistence of relatively unaltered plagioclase with amphibolitized pyroxene suggests a temperature increase with depth, and that (3) most secondary minerals identified during Leg 140 are similar to those described by Alt et al. (1989) in the upper part of the sheeted dike complex. On Leg 140 an additional alteration mineral, serpentine, was identified as a secondary phase, replacing olivine (Dick, Erzinger, Stokking, et al., 1992). Our investigation by electron microprobe reveals, however, that the "serpentine" (colorless with first-order gray birefringence) is a mineraloid; deweylite, a mixture of serpentine and stevensite (Lapham, 1961; Faust and Fahey, 1962) or a mixture of talc and serpentine (Bish and Brindley, 1978; Speakman and Majumbar, 1971).

METHODS

Detailed petrographic study of polished thin sections preceded the chemical analyses of secondary minerals. The chemical composition of alteration minerals was determined by an ETEC electron microprobe, equipped with an energy dispersive system, at the Department of Geology, University of Toronto. Operating conditions were 20 kV accelerating voltage and 50 nA beam current. Results are shown in Tables 1, 2, and 3.

¹Erzinger, J., Becker, K., Dick, H.J.B., and Stokking, L.B. (Eds.), 1995. *Proc. ODP, Sci. Results*, 137/140: College Station, TX (Ocean Drilling Program).

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MINERALOGY AND TEXTURE

In the most extensively altered diabase, olivine is completely replaced by sheet silicates (listed below) and clinopyroxene is replaced by actinolite, actinolitic hornblende or magnesiohornblende. Ilmenomagnetite is generally replaced by titanite and some of the igneous plagioclase is partly recrystallized to albite \pm chlorite and/or amphibole. Other minor alteration minerals include epidote, anhydrite, secondary magnetite, sulfides, prehnite, laumontite, and quartz (Dick, Erzinger, Stokking, et al., 1992). In addition to the above minor phases, fine-grained calcite was identified within plagioclase, as well as fine-grained titanium oxide (rutile, anatase or brookite) which formed from the breakdown of titanite. Although some rocks are pervasively altered, for the most part, the igneous texture of the diabase is well preserved. The most extensive alteration in the dikes was noted in veins and vein halos, and localized alteration patches. These patches consist predominantly of amphibole and chlorite (Dick, Erzinger, Stokking, et al., 1992).

Several generations of chlorite and actinolite veins in the SDC suggests their crystallization during multiple hydrothermal episodes. Crack-seal mechanism is evident where different generations of chlorite-actinolite veins occupy the same fractures (Dick, Erzinger, Stokking, et al., 1992).

The following section will describe in some detail replacement textures in olivine and the alteration minerals after olivine.

Alteration of Olivine

Olivine occurs in the diabase as fresh, partly or completely altered phenocrysts (1–5 mm diameter), and as partly or completely altered grains in the groundmass. The replacement minerals after olivine include talc (tlc), chlorite (chl), deweylite (dew), mixed layer chlorite-smectite (ml), actinolite (act), magnetite (mt), ferric oxide (Fe^{3+}), pyrite (py), chalcocopyrite (cp), and quartz (qtz). Replacement assemblages fall into two groups: Al-free and Al-bearing.

Al-free group:

1. tlc + mt \pm py \pm cp
2. dew + Fe^{3+} -oxide
3. dew + mt + Fe^{3+} -oxide \pm py \pm cp
4. tlc + dew + mt + Fe^{3+} -oxide \pm py \pm cp

Al-bearing group:

5. chl \pm qtz
6. chl \pm mt \pm py \pm cp
7. chl + act \pm py \pm cp
8. ml \pm mt

9. ml \pm mt \pm py \pm cp

10. tlc + ml + mt \pm Fe^{3+} -oxide \pm py \pm cp

The above assemblages have all been identified as replacement after olivine, and a combination of two or more assemblages may be present within one single phenocryst. Subdivision of the above two groups is based on Al_2O_3 content, because Mg-rich, Al-free minerals such as talc, serpentine and deweylite can crystallize from the hydration of olivine, but Al-bearing replacement minerals require the addition of Al, presumably from the breakdown of Al_2O_3 -bearing phases such as plagioclase.

Replacement Textures in Olivine

Talc + magnetite commonly occur as alteration rims on olivine, and as fractures within the grains (Pl. 1A, -B). This assemblage is present in olivine phenocrysts and in groundmass olivine throughout most of the 350 m section of the SDC. The replacement of groundmass olivine by talc is generally more extensive than of the phenocrysts. Subsequent alteration of olivine gave rise to the partial replacement of talc by deweylite and serpentine. Deweylite is a chaotic mixture of serpentine and stevensite. Where alteration is incomplete and talc and deweylite coexists, the latter is intercalated with, or forms rims on islands of talc aggregates (Pl. 1C). Where talc is restricted to olivine rims, the center of the grain may be replaced by chlorite, mixed layer chlorite, and/or deweylite. In some cases, olivine is completely pseudomorphed by chlorite, and the earlier presence of talc is indicated only by small inclusions of talc aggregates in chlorite, or by the presence of fine-grained relict magnetite on olivine rims and in olivine fractures. The presence of quartz and deweylite inclusion in the center of chloritized olivine suggests the replacement of deweylite by chlorite (Pl. 1D). Quartz probably formed during the replacement of the SiO_2 -rich deweylite by the SiO_2 -poor chlorite.

All of the above alteration assemblages in olivine may be partially or completely replaced by acicular, sub- to euhedral amphibole. Although minor amphibole needles preferentially replace chlorite altered olivine, some also crystallized at the expense of talc and deweylite. The complete replacement of olivine by amphibole occurs only in extensively amphibolitized rocks. Figure 1 is a schematic sketch demonstrating the paragenetic sequence of replacement assemblages in olivine.

Texture and Chemistry of the Al-free Minerals (Talc, Deweylite, and Serpentine)

The Al-free sheet silicates that replace olivine are talc, serpentine and deweylite. Deweylite was described by Lapham (1961) as a "dioctahedral modification of antigorite," by Bish and Brindley (1978),

Table 1. Microprobe analyses of deweylite, serpentine, and talc (Leg 140, Hole 504B).

Sample:	140-12	140-12	140-13	140-13	140-14	140-14	140-14	140-14	140-17	140-17	140-17	140-17	140-17
Core, section:	200R-3	200R-3	200R-1	200R-1	200R-1	200R-1	200R-1	200R-1	208R-1	208R-1	208R-1	208R-1	208R-1
Interval (cm):	7-9	7-9	83-85	83-85	130-132	130-132	130-132	130-132	14-16	14-16	14-16	14-16	14-16
Depth (mbsf):	1731.8	1731.8	1729.5	1729.5	1729.9	1729.9	1729.9	1729.9	1778.2	1778.2	1778.2	1778.2	1778.2
Mineral:	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.	Dew.
SiO ₂	50.52	50.10	50.30	51.07	51.93	51.18	53.27	51.96	52.68	52.98	49.97	55.28	55.64
FeO*	4.66	3.58	4.69	5.95	3.68	3.84	4.69	4.40	4.26	2.45	3.65	2.59	5.18
MgO	31.81	33.34	31.74	30.27	33.47	32.82	32.97	31.01	34.87	32.85	32.26	30.38	27.79
CaO	0.23	0.01	0.21	0.30	0.00	0.00	0.00	0.00	0.17	0.15	0.16	0.00	0.00
NiO	0.00	0.00	0.25	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	87.22	87.03	87.19	87.81	89.08	87.84	90.93	87.37	91.98	88.43	86.04	88.25	88.61
Si	4.634	4.582	4.627	4.680	4.637	4.638	4.653	4.729	4.575	4.722	4.625	4.897	4.960
Fe	0.357	0.273	0.359	0.455	0.275	0.291	0.344	0.335	0.309	0.182	0.283	0.193	0.385
Mg	4.351	4.545	4.351	4.136	4.455	4.435	4.311	4.207	4.515	4.361	4.451	4.015	3.693
Ca	0.022	0.001	0.021	0.030	0.000	0.000	0.000	0.000	0.015	0.014	0.016	0.000	0.000
Ni	0.000	0.000	0.019	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Notes: FeO* = total Fe; Dew. = deweylite; Serp. = serpentine. Al_2O_3 was analyzed for but below detection limit. Deweylite based on 14 oxygens, serpentine recalculated to 14 oxygens, and talc based on 22 oxygens.

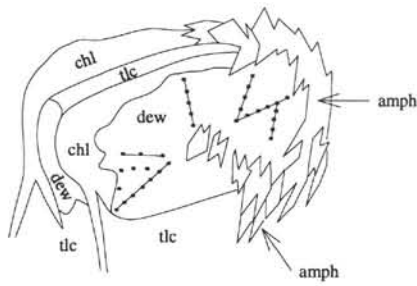


Figure 1. Schematic diagram of replacement assemblages after olivine (Sample 140-504B-208R-1, 14–16 cm). Dew = deweylite; tlc = talc; chl = chlorite; amph = amphibole. Black spots are magnetite. Interpreted paragenetic sequence: tlc, dew, chl, amph.

Speakman and Majumbar (1971) as intergrowths of talc and serpentine, and more accurately by Faust and Fahey (1962) as a mineraloid, consisting of a mixture of serpentine and Al-free stevensite (trioctahedral smectite). The low totals in the relatively pure deweylites (Table 1), coupled with low first order birefringence implies the intergrowth of serpentine with an Al-free (trioctahedral) smectite rather than with talc.

The replacement of olivine by talc progresses inward to core. Colorless, highly birefringent talc most commonly occurs on the rim and along the fractures of olivine phenocrysts (Pl. 1A, -B). As the talc structure cannot accommodate most of the iron released from the breakdown of olivine, Fe is taken up by contemporaneously forming fine-grained, anhedral magnetite (Pl. 1A). Magnetite also occurs in fractures, outlining the fractures in olivine phenocrysts. Talc is generally fine-grained on olivine rims, but when alteration is extensive, it coarsens toward the cores of olivine phenocrysts. Groundmass olivine generally tends to be more extensively replaced by talc and magnetite than the olivine phenocrysts.

Deweylite partly or completely replaces olivine and talc (Pl. 2A, -B). When replacement is incomplete, deweylite is interstitial to talc, or encloses islands of talc within olivine phenocrysts (Pl. 1C). Deweylite has a "swollen" texture (Pl. 2A) in comparison to talc. Unlike talc, which generally forms narrow rims on olivine, or progressively replaces olivine from rim to core, deweylite also occurs in olivine cores, forming small domains within the phenocrysts. Optical distinction between deweylite and pure serpentine is not possible, but lizardite and clinochrysotile are considered to be the most common serpentine polymorphs that comprise deweylite (Faust and Fahey, 1962). Mesh texture (Pl. 2B) and inter-penetrating textures (Pl. 2C), typical of serpentine polymorphs, are commonly observed. Magnetite is relatively rare in deweylite altered olivine, but subrounded anhedral grains of Fe³⁺ oxides are abundant (Pl. 2D). Small magnetite

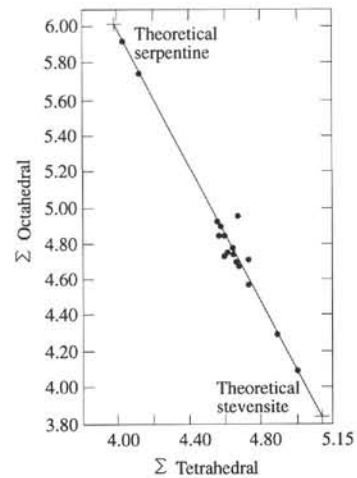


Figure 2. Microprobe analyses of deweylite and serpentine from Hole 504B, Leg 140, are plotted on the diagram of Faust and Fahey (1962). Cations were calculated on basis of 14 oxygens. Line defines the field of deweylite as determined by Faust and Fahey (1962). All data points are from deweylite-serpentine mixtures replacing olivine.

inclusions within Fe³⁺ oxides suggests that some of these oxides may have formed from the oxidation of preexisting magnetite.

The chemical composition and stoichiometry of deweylites in the SDC, Hole 504B are shown in Table 1. For comparison, deweylite compositions from Lapham (1961, p. 175) and Faust and Fahey (1962, p. 19, no. F48) are also shown in Table 1. Note that the ratio of tetrahedral cations (Si, Al^{IV}) to octahedral cations (Al^{VI}, Mg, Fe) in deweylite is approximately 1:1, in serpentine and chlorite, it is 2:3, in dioctahedral smectites (i.e., montmorillonite), it is 2:1 and in trioctahedral smectites (i.e., stevensite) and talc, it is 4:3. As shown in Table 1, the stoichiometry of deweylite (based on 14 oxygen ions) is very different from pure serpentine. Based on the sum of tetrahedral and octahedral cations, the fields of theoretical serpentine and stevensite are shown on Figure 2. Most deweylites from Leg 140 plot on the central part of the line connecting the serpentine and stevensite fields, suggesting that deweylites are made up of an equal mixture of the two phyllosilicates. Microprobe analyses of deweylites <10 μ size) in olivine reveal coexisting serpentine and stevensite compositions within different domains of the same grain on the micron scale. The serpentine have relatively high Fe contents compared to those reported by Deer et al. (1978), but are similar in composition to some Fe-rich serpentine in peridotites, described by Wicks and Plant (1983). Our results indicate that much of the alteration minerals optically identified

Table 1 (continued).

Sample:	140-27	140-27	140-27			140-12	140-12	140-13	140-24	140-14	140-17
Core, section:	226R-1	226R-1	226R-1	Faust &		200R-3	200R-3	200R-1	227R-1	200R-1	208R-1
Interval (cm):	16–20	16–20	16–20	Fahey	Lapham	7–9	7–9	83–85	20–25	130–132	14–16
Depth (mbsf):	1912.9	1912.9	1912.9	1962	1961	1731.8	1731.8	1729.5	1929.8	1729.9	1778.2
Mineral:	Dew.	Dew.	Dew.	DewF-48	Dew.	Talc	Talc	Talc	Talc	Serp.	Serp.
SiO ₂	48.20	52.47	48.20	47.00	52.43	62.21	62.00	62.51	61.89	41.67	45.18
FeO*	2.61	3.02	2.53	5.50	2.16	1.68	3.84	4.70	4.00	7.50	6.20
MgO	32.78	34.36	36.65	29.70	31.62	30.27	28.80	28.48	28.89	36.55	38.42
CaO	0.00	0.00	0.00	0.20	0.00	0.00	0.22	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00
Total	83.59	89.85	87.38	82.40	86.37	94.16	94.86	95.69	94.78	85.72	89.80
Si	4.576	4.626	4.403	4.800	4.667	8.011	8.000	8.029	7.999	4.048	4.140
Fe	0.207	0.222	0.191	0.450	0.249	0.179	0.429	0.506	0.432	0.784	0.476
Mg	4.640	4.517	4.991	4.330	4.500	5.800	5.536	5.454	5.567	5.294	5.246
Ca	0.000	0.000	0.000	0.020	0.000	0.000	0.030	0.000	0.000	0.000	0.000
Ni	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	0.000

Table 2. Microprobe analyses of chlorites (Leg 140, Hole 504B).

Sample:	140-20	140-24	140-19	140-23	140-24	140-10	140-24	140-10	140-10	140-10	140-10	140-25
Core, section:	176R-1	227R-1	211R-1	225R-2	227R-1	189R-1	227R-1	189R-1	189R-1	189R-1	189R-1	237R-1
Interval (cm):	100-103	20-25	75-77	33-35	20-25	17-19	20-25	17-19	17-19	17-19	17-19	3-5
Depth (mbsf)	1596.4	1924.8	1799.3	1914	1924.8	1651-2	1924.8	1651.2	1651.2	1651.2	1651.2	1983.8
Type:	rep pyx	rep plag	vein	vein	interst	rep ol	rep ol	rep ol	rep ol	rep ol	rep ol	qtz-chl
SiO ₂	29.23	29.31	31.42	29.01	29.58	27.28	30.87	28.84	28.66	30.71	26.87	28.29
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.08	0.02
Al ₂ O ₃	17.95	18.28	17.52	17.93	18.08	17.41	17.51	16.61	17.69	18.41	15.98	18.60
FeO*	22.75	17.85	18.35	22.03	16.82	31.71	17.05	24.64	23.51	22.40	33.32	20.05
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.03	0.22	0.12	0.08
MgO	16.98	21.73	19.20	18.56	22.40	11.87	24.17	15.64	17.22	18.03	10.95	20.80
CaO	0.47	0.00	0.75	0.00	0.00	0.00	0.00	0.37	0.29	0.42	0.24	0.05
Total	87.38	87.17	87.24	87.53	86.88	88.27	89.60	86.3	87.4	90.23	87.56	87.89
Si	6.060	5.937	6.349	5.981	5.977	5.895	6.045	6.018	5.973	6.128	5.930	5.761
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.006	0.014	0.003
Al ^{IV}	2.448	2.032	2.521	2.337	2.286	2.331	2.086	2.248	2.318	2.456	2.087	2.225
Fe	3.945	3.024	3.100	3.799	2.843	5.732	2.792	4.453	4.098	3.738	6.151	3.414
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.005	0.038	0.023	0.013
Mg	5.240	6.563	5.782	5.704	6.749	3.824	7.055	5.038	5.350	5.362	3.603	6.311
Ca	0.105	0.000	0.161	0.000	0.000	0.000	0.000	0.087	0.064	0.092	0.056	0.012
Fe/Fe+Mg	0.43	0.32	0.35	0.40	0.30	0.60	0.28	0.47	0.43	0.41	0.63	0.35

Notes: FeO* = total Fe, pyx = pyroxene, plag = plagioclase, ol = olivine, qtz = quartz, chl = chlorite, interst = interstitial, rep = replacing. Number of ions based on 28 oxygens.

as colorless smectite and/or serpentine during Leg 140 (Dick, Erzinger, Stokking, et al., 1992), is probably the serpentine-stevensite mixture, deweylite.

Texture and Chemistry of the Al-bearing Minerals (Chlorite and Mixed-layer Chlorite)

The presence of chlorite in the SDC is often accompanied by the partial replacement of plagioclase by albite (Dick, Erzinger, Stokking et al., 1992).

A general decrease in the abundance of chlorites (as replacement minerals and veins) and mixed layer chlorites (as replacement of olivine) with depth was noted in the dikes during Leg 140 (Dick, Erzinger, Stokking, et al., 1992). Textural evidence suggests that some of the chlorites crystallized from the breakdown of previous alteration minerals such as talc, serpentine and deweylite. The replacement of olivine by chlorite generally progresses from rim to core, although some talc-rimmed olivine have chloritic centers. Where there is complete replacement of olivine by chlorite, inclusions of deweylite and/or quartz may be present in the center of the grains (Pl. 1D). The presence of fine-grained magnetite rims in chlorite altered olivine indicates the earlier partial replacement of olivine by an Fe-poor mineral, such as talc, serpentine or deweylite. The chlorites are generally colorless in plane polarized light and have brown, dark blue or anomalous blue birefringence.

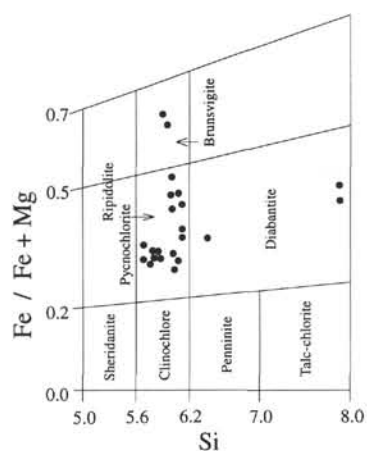


Figure 3. Chlorite compositions (Hole 504B, Leg 140) plotted on the classification diagram of Hey (1954).

Replacement chlorites after olivine, clinopyroxene, plagioclase, actinolite, and interstitial chlorite, as well as chlorite veins, were analyzed by electron microprobe. Chemical analyses of selected samples are shown on Table 2. Our data suggests that chlorite composition is partly influenced by the type of minerals replaced. The variable Fe/Fe+Mg ratios in chlorite after olivine (0.30–0.63) probably reflects the involvement of randomly distributed fine-grained magnetite during the chlorite-forming reaction. Figure 3 demonstrates that most chlorites in this study plot on the pycnochlorite and brunsvigite fields on Hey's diagram (Hey, 1954).

Mixed-layer chlorite-smectite were optically identified and analyzed by electron microprobe. Their olive-green or tan color, middle-second order birefringence and high SiO₂ content suggest that their optical properties and composition (Table 2) are comparable to groups 4 and 5 of the mixed-layer chlorites described by Alt et al. (1985). They were found to be too fine-grained to obtain a clean separate for X-ray diffraction, but plot on the diabantite field (Fig. 3). Although the chlorites in this section of the SDC have compositional ranges similar to chlorites previously reported by Alt et al. (1985) from Leg 83, there are some differences as well. In the present study Fe/Fe+Mg ratios in all chlorite are above 0.30, whereas in rocks from Leg 83 many have ratios (particularly the mixed-layer chlorites) in the 0.20–0.30 range. This is consistent with observations of Alt et al. (1985) that the smectite component in chlorites decreases with depth.

Amphiboles as Replacement Silicates and Veins

The replacement of olivine by amphibole occurs only in the most extensively amphibolitized rocks where it is associated with the breakdown of titanomagnetite to titanite. Most of these rocks show evidence of fracturing and the fractures are filled with amphibole ± chlorite veins. Amphibole is always a late replacement mineral after olivine, although locally it may be altered to chlorite.

In the lower section of the SDC (1625–2000 mbsf), amphibole composition ranges from actinolite to ferroactinolite to magnesiohornblende (Fig. 4), similar to those previously reported from Leg 83 and from Leg 111 (Alt et al., 1985; Ishizuka, 1989). Detailed petrographic observations combined with microprobe analysis indicate some correlation between the mode of occurrence and the chemistry of various amphibole generations. Table 1 and Figure 4 demonstrate that replacement after clinopyroxene and chlorite, mixed-layer chlorite generally plot in the actinolite-ferroactinolite field, whereas interstitial amphiboles between phenocrysts, as well as most veins, plot within or close to the actinolitic hornblende and magnesiohornblende fields.

Table 2 (continued).

Sample:	140-25	140-25	140-24	140-24	140-24	140-24	140-24	140-24	140-10	140-10
Core, section:	237R-1	237R-1	227R-1	227R-1	227R-1	227R-1	227R-1	227R-1	189R-1	189R-1
Interval (cm):	3-5	3-5	20-25	20-25	20-25	20-25	20-25	17-19	17-19	17-19
Depth (mbsf)	1983.8	1983.8	1924.8	1924.8	1924.8	1924.8	1924.8	1924.8	1651.2	1651.2
Type:	qtz-chl	qtz-chl	rep ol	rep ol	rep ol	rep ol	rep ol	rep ol	rep ol	rep ol
SiO ₂	29.20	29.92	28.98	28.71	29.10	28.68	28.99	29.93	40.70	41.51
TiO ₂	0.08	0.03	0.00	0.00	0.03	0.00	0.00	0.05	0.00	0.00
Al ₂ O ₃	16.43	17.16	18.88	18.40	18.91	17.69	18.58	18.94	14.22	16.62
FeO [†]	19.28	20.01	17.86	18.19	18.00	18.32	18.12	18.09	15.80	16.32
MnO	0.19	0.11	0.14	0.19	0.08	0.06	0.17	0.04	0.00	0.00
MgO	19.82	19.50	22.65	22.84	22.04	21.22	22.61	22.67	15.90	14.20
CaO	0.57	0.27	0.03	0.04	0.09	0.10	0.06	0.05	1.31	1.00
Total	85.57	87.00	88.54	88.37	88.25	86.07	88.53	89.77	87.93	89.65
Si	6.103	6.132	5.772	5.766	5.822	5.897	5.793	5.881	7.880	7.794
Ti	0.003	0.004	0.000	0.000	0.005	0.000	0.000	0.007	0.000	0.000
Al ^{IV}	2.150	2.278	2.204	2.121	2.281	2.185	2.130	2.267	3.126	3.472
Fe	3.370	3.429	2.975	3.056	3.012	3.150	3.028	2.972	2.558	2.562
Mn	0.028	0.019	0.023	0.032	0.013	0.010	0.029	0.006	0.000	0.000
Mg	6.175	5.956	6.726	6.837	6.573	6.503	6.735	6.639	4.587	3.974
Ca	0.128	0.060	0.006	0.008	0.018	0.020	0.014	0.012	0.272	0.201
Fe/Fe+Mg	0.36	0.37	0.3	0.31	0.32	0.33	0.31	0.31	0.36	0.39

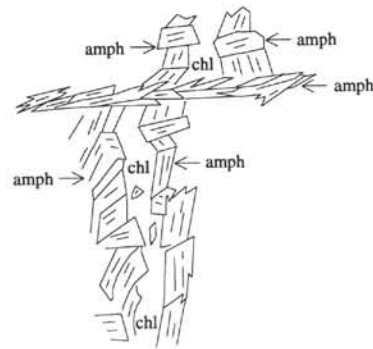
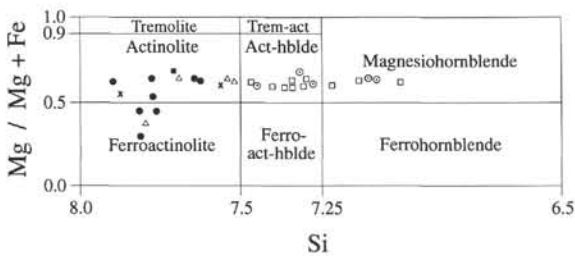


Figure 4. Microprobe analyses of amphiboles (Hole 504B, Leg 140) plotted on the amphibole classification diagram of Leake (1978). Solid circle = replacement of clinopyroxene; open square = veins; x = relict and late veins from Sample 140-504B-186R-1, 57–60 cm; solid square = relict vein from Sample 140-504B-208R-1, 14–16 cm; circle with dot = interstitial; and triangle = replacement after chlorite, mixed-layer chlorite.

Figure 5. Schematic diagram of amphibole vein intruded in center by chlorite; it is also crosscut and offset by late amphibole vein (Sample 140-504B-186R-1, 57–60 cm). Chl = chlorite; amph = amphibole.

The variable FeO (13–31 wt%) and TiO₂ (1.0–1.3 wt%) concentrations in amphibole phenocrysts suggest a localized control of the igneous mineralogy on amphibole chemistry. As the crystallization of amphibole is commonly associated with the breakdown of titanomagnetite to titanite (Alt et al., 1986), Fe-enrichment in amphiboles adjacent to titanite (i.e., Sample 140-504B-189R-1, 17–19 cm), is not surprising. This scenario could also account for their variable TiO₂ content. That amphiboles probably crystallized during several hydrothermal cycles is supported by textural evidence such as crack-seal texture and offset veins and compositional differences between relict and crosscutting veins (Fig. 5) within the same rock (i.e., Sample 140-504B-186R-1, 57–60 cm; Table 3 and Fig. 4).

On the basis of texture and mineral chemistry, we identified at least two amphibole generations in the dikes. Crosscutting veins in the same rock have different compositions; that is, in a relict (r.) vein (Sample 140-504B-186R-1, 57–60 cm) Si = 7.584 and Al₂O₃ = 3.70 wt%, whereas in a late (l.) crosscutting vein in the same rock, Si = 7.872 and Al₂O₃ = 1.38 wt%. Chemical differences between different vein generations (relict and crosscutting veins) are also evident in Sample 140-504B-208R-1, 14–16 cm (Table 3). The small but consistent chemical differences between what has been identified as first and second generation amphiboles in this study are probably due to somewhat different conditions during their crystallization, such as changes in temperature, rock porosity, and the extent of water:rock interaction.

Figure 6 (modified after Dick, Erzinger, Stokking, et al., 1992) demonstrates the occurrence of different alteration minerals through

the 2-km-thick crust at Hole 504B. Calcite was added to the diagram, and serpentine was replaced by “deweylite,” emphasizing that “serpentine” represents the mixture of serpentine and Al-free stevensite.

DISCUSSION

The hydrothermal evolution of olivine in the lowermost 350 m section of the SDC in Hole 504B is well preserved by replacement minerals. The two distinct groups of Al-free (talc, deweylite) and Al-rich (chlorite, mixed-layer chlorite) assemblages suggest a complex series of alteration events.

The replacement of olivine by talc and magnetite is interpreted to have occurred during initial cooling of the dikes. Textural evidence such as narrow talc rims or talc-filled fractures in olivine suggests limited seawater penetration into the dikes during the partial breakdown of olivine to talc + magnetite. Subsequent replacement of talc by deweylite and the partial or complete replacement of fresh olivine centers by deweylite and Fe³⁺ oxides indicates the continuing penetration of seawater into cooling dikes. Crystallization of the aluminum-free sheet silicates suggests that plagioclase remained stable during the early stages of alteration. This would be consistent with relatively high temperatures, limited porosity and fluid supply during the early stages of alteration, as plagioclase readily breaks down to albite in the presence of neutral to high pH fluid at or below 400°C (Martin, 1969). We do not have a good control on the temperature of

Table 3. Microprobe analyses of amphiboles (Leg 140, Hole 504B).

Sample:	140-9	140-9	140-9	140-10	140-10	140-10	140-14	140-17	140-17	140-17	140-17	140-17	140-17	140-17
Core, section:	186R-1	186R-1	186R-1	189R-1	189R-1	189R-1	200R-1	208R-1	208R-1	208R-1	208R-1	208R-1	208R-1	208R-1
Interval (cm):	57-60	57-60	57-60	17-19	17-19	17-19	130-132	14-16	14-16	14-16	14-16	14-16	14-16	14-16
Depth (mbsf):	1626.8	1626.8	1626.8	1651.2	1651.2	1651.2	1729.9	1778.2	1778.2	1778.2	1778.2	1778.2	1778.2	1778.2
Type:	r. vein	rep cpx	l. vein	rep cpx	rep cpx	rep ol	interst	r. vein	interst	interst	interst	vein	vein	vein
SiO ₂	52.70	53.15	53.30	50.94	52.20	52.21	50.58	53.41	49.00	52.36	49.06	51.98	51.18	47.73
TiO ₂	0.24	0.30	0.00	0.32	0.25	0.00	0.00	0.57	1.15	0.00	1.34	0.68	0.27	0.31
Al ₂ O ₃	3.70	2.41	1.38	2.55	2.95	2.12	7.26	1.89	7.85	5.90	8.10	5.05	5.87	7.86
FeO*	15.45	14.02	17.95	31.05	23.72	18.57	17.70	12.53	14.50	15.80	13.79	14.81	15.52	14.45
MnO	0.24	0.27	0.33	0.49	0.44	0.00	0.38	0.00	0.17	0.21	0.16	0.21	0.23	0.26
MgO	14.58	15.55	13.20	6.55	10.94	13.77	17.45	16.99	13.97	14.18	14.41	14.35	13.90	13.94
CaO	11.80	12.07	11.09	6.66	6.76	10.20	4.46	11.51	11.06	10.48	10.82	11.29	10.10	11.01
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.00	0.00	0.00	0.00	1.16
Cl	0.09	0.30	0.10	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.19	0.25	0.13	0.00
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.03
Total	98.80	98.07	97.35	98.56	97.26	96.87	97.83	97.10	98.73	98.93	97.87	98.62	97.20	96.75
Si	7.584	7.668	7.872	7.801	7.805	7.740	7.272	7.703	7.074	7.479	7.106	7.469	7.409	7.021
Ti	0.026	0.055	0.000	0.037	0.028	0.000	0.000	0.062	0.125	0.000	0.145	0.074	0.029	0.017
Al ^{IV}	0.416	0.332	0.128	0.199	0.195	0.260	0.728	0.297	0.926	0.521	0.894	0.531	0.591	0.979
Al ^{VI}	0.217	0.079	0.110	0.263	0.324	0.112	0.502	0.025	0.411	0.472	0.475	0.323	0.411	0.389
Fe	1.860	1.693	2.211	3.978	2.966	2.304	2.117	1.512	1.752	1.807	1.657	1.789	1.880	1.783
Mn	0.029	0.035	0.040	0.064	0.055	0.000	0.044	0.000	0.021	0.026	0.210	0.027	0.027	0.033
Mg	3.128	3.344	2.889	1.495	2.439	3.040	3.740	3.654	3.008	3.022	3.087	3.075	2.994	3.066
Ca	1.817	1.866	1.754	1.083	1.083	1.622	0.687	1.778	1.712	1.605	1.667	1.740	1.719	1.741
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.208	0.000	0.000	0.000	0.000	0.333
Cl	0.023	0.075	0.026	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.047	0.060	0.033	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.003
Mg/Mg+Fe	0.63	0.66	0.57	0.27	0.45	0.43	0.64	0.71	0.63	0.62	0.65	0.63	0.61	0.63

Notes: FeO* = total Fe, r. vein = relict vein, l. vein = late vein, cpx = clinopyroxene, ml = mixed-layer chlorite, chl = chlorite, ol = olivine, rep = replacement, interst = interstitial. Number of ions based on 23 oxygens.

crystallization for talc in these rocks. However, the stability field of talc and forsterite in the MgO-SiO₂-H₂O system is in the range of 500°–600°C (O'Hanley et al., 1989), and below 500°C they break down to form antigorite. This would support our observations that the replacement of olivine by talc occurred at the initial stage of cooling, whereas its breakdown to the more hydrous sheet silicates (i.e., "deweylite") occurred during a further decrease in temperature and possi-

bly an increase in rock porosity (greater fluid:rock interaction). The stability field of deweylite is not well known, but as it occurs in weathered rocks, in open cavities, fractures, commonly replacing serpentine or other minerals, it is thought to be a low temperature (<100°C) mineral (Lapham, 1961; Faust and Fahey, 1962). Based on field relationships (Lapham, 1961; Faust and Fahey, 1962) it has been suggested that they generally form at temperatures at around 50°C (Wenner and Taylor, 1972). However, the replacement of deweylite by amphibole, and the present temperature in the hole demonstrates that deweylite (serpentine-stevensite) can form in greenschist facies conditions, where temperatures are much higher than previously estimated from the isotopic studies of altered peridotite (Wenner and Taylor, 1972).

Al-rich replacement minerals after olivine are predominantly chlorite and some mixed layer chlorite. They postdated talc and deweylite as suggested by the partial breakdown of the Al-free sheet silicates and their replacement by these Al-bearing assemblages. Unlike talc and deweylite, chlorite is not restricted to the replacement of olivine, but commonly occurs interstitially, replacing the matrix and forming veins. The occurrence of fine-grained albite in chloritized rocks suggests that the replacement of olivine by the Al-bearing group and the development of chlorite veins was contemporaneous with the localized partial replacement of plagioclase by albite. As chlorite alteration is associated with fractures in the dikes (i.e., chlorite veins), this alteration must have occurred at greater fluid:rock interaction. Small differences in chlorite chemistry and crosscutting relationships between veins suggests that chlorite alteration was either a continuous process, during cooling and fracturing (shrinkage cracks) of the dikes, or there was more than one episode of chlorite alteration.

Multiple amphibole vein generations is evident from textural and compositional differences between earlier and later veins, as well as from the crack-seal texture in some veins. However, the temporal relationship between amphibole and chlorite veins is not straightforward. The common occurrence of composite (amphibole and chlorite) veins as described by Dick, Erzinger, Stokking, et al. (1992) and their crosscutting relationship is interpreted to reflect multiple episodes of dike intrusion and the subsequent and repeated fracturing of the dikes.

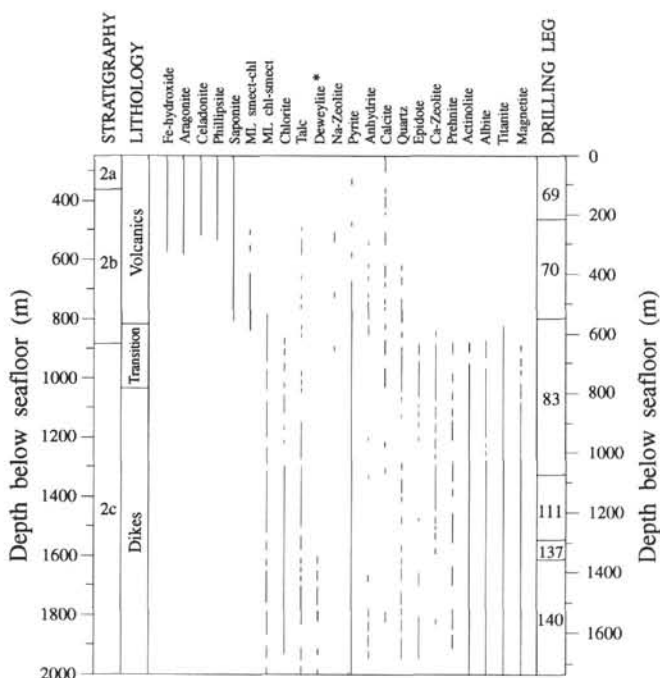


Figure 6. Distribution of secondary minerals with depth, Hole 504B (after Dick, Erzinger, Stokking, et al., 1992). Calcite is added to the diagram, and serpentine is replaced by deweylite*, which is a mixture of serpentine and Al-free stevensite.

Table 3 (continued).

140-17 208R-1 14-16 1778.2 vein	140-17 208R-1 14-16 1778.2 vein	140-17 208R-1 14-16 1778.2 vein	140-17 208R-1 14-16 1778.2 vein	140-17 208R-1 14-16 1778.2 vein	140-17 208R-1 14-16 1778.2 vein	140-19 211R-1 75-77 1799.3 rep cpx	140-19 211R-1 75-77 1799.3 rep cpx	140-19 211R-1 75-77 1799.3 vein	140-21 191R-1 136-139 1665.0 rep ml	140-21 191R-1 136-139 1665.0 rep cpx	140-23 225R-2 33-35 1914.0 rep chl	140-23 225R-2 33-35 1914.0 rep pyx	140-24 227R-1 20-25 1924.8 interst	140-24 227R-1 20-25 1924.8 rep ml	140-24 227R-1 20-25 1924.8 rep ml
51.20	51.12	50.21	49.11	50.61	51.40	52.65	54.60	49.90	51.24	51.86	52.15	53.45	52.28	53.48	52.67
0.31	0.61	0.34	0.32	0.00	0.39	0.27	0.00	0.67	0.45	0.28	0.00	0.36	0.00	0.00	0.00
7.10	6.68	6.15	7.38	6.45	5.51	2.12	1.01	7.10	2.16	2.65	4.70	3.35	5.49	2.56	4.94
13.49	15.34	14.01	14.49	15.22	14.05	13.20	15.70	14.60	28.50	18.67	14.90	13.80	13.90	14.41	15.02
0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.47	0.18	0.18	0.00	0.00	0.00	0.00
15.70	13.64	14.78	14.40	13.77	15.16	13.67	14.63	13.90	7.77	11.42	14.75	14.90	16.20	15.30	14.42
10.74	10.31	12.17	11.71	12.16	11.99	15.69	11.75	12.03	7.79	11.74	11.30	11.67	10.92	12.48	11.43
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.22	0.16	0.16	0.26	0.14	0.17	0.00	0.00	0.21	0.26	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
98.76	98.10	97.82	97.67	98.35	98.67	97.77	97.69	98.59	98.64	96.80	97.98	97.53	98.79	98.23	98.48
7.347	7.374	7.279	7.152	7.322	7.362	7.666	7.906	7.205	7.769	7.744	7.536	7.699	7.300	7.698	7.537
0.540	0.066	0.036	0.034	0.000	0.043	0.030	0.000	0.069	0.053	0.033	0.000	0.039	0.000	0.000	0.000
0.653	0.626	0.721	0.848	0.678	0.638	0.334	0.094	0.795	0.231	0.256	0.464	0.301	0.700	0.302	0.463
0.549	0.514	0.325	0.418	0.417	0.282	0.031	0.081	0.418	0.155	0.184	0.338	0.266	0.136	0.233	0.370
1.884	1.850	1.699	1.765	1.841	1.692	1.608	1.916	1.760	3.615	2.333	1.793	1.663	1.635	1.734	1.797
0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.064	0.22	0.023	0.000	0.000	0.000	0.000
2.885	2.932	3.194	3.126	2.970	3.258	2.968	3.163	2.990	1.757	2.54	3.178	3.184	3.454	3.283	3.075
1.652	1.594	1.891	1.828	1.884	1.854	2.449	1.836	1.857	1.335	1.88	1.722	1.810	1.662	2.010	1.765
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.054	0.041	0.039	0.063	0.034	0.042	0.000	0.000	0.052	0.067	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.60	0.61	0.65	0.64	0.62	0.66	0.65	0.62	0.62	0.33	0.52	0.64	0.66	0.68	0.65	0.63

Although in this study we distinguished between different alteration episodes, collectively these "episodes" must have occurred within a long-lived hydrothermal system which has been active during the entire evolution of the SDC. The repetitive nature of these episodes is evident from crosscutting relationships between chlorite and amphibole veins.

CONCLUSIONS

Replacement textures and alteration minerals in olivine preserve the hydrothermal evolution of the 350-m section of the SDC drilled in Hole 504B. Based on mineralogy, mineral chemistry, and texture, the following sequence of hydrothermal events is suggested:

1. The alteration of olivine to talc occurred during incipient cooling of the dikes, as a small amount of seawater was entrapped in the rocks during crystallization.
2. The subsequent breakdown of talc to serpentine-stevensite (deweylite) reflects further cooling and increasing fluid circulation in the dikes.
3. Shrinkage cracks developed in the cooling dikes, forming localized channels for fluid penetration. This resulted in the localized, partial breakdown of plagioclase to albite and the uptake of Al_2O_3 by chlorite. Chlorite (\pm mixed-layer chlorite) partly replaced earlier Al-free sheet silicates in olivine and occur as vein fillings.
4. As new dikes were injected, the influx of new magma and the buildup of fluid pressure re-fractured the earlier dikes, reopening fractures such as shrinkage cracks (i.e., crack-seal texture) as well as creating new ones. The localized circulation of hot fluids along fractures resulted in the development of amphibole veins, amphibole alteration of matrix (i.e., "interstitial"; Table 3) and the breakdown of titanomagnetite to titanite in the vicinity of the veins. As the fresh magma cooled, the replacement cycle 1 to 3 continued in the newly solidified dikes. The above alteration cycle, which is probably repeated with the injection of each new set of dikes, gave rise to the offset veins, the crack-seal texture in veins, the several generations of chlorite and amphibole veins and to replacement of pyroxene phenocrysts and previously altered olivine phenocrysts in the dikes.

5. We suggest that the hydrothermal evolution of the dikes was complete by the time the SDC moved away from the ridge axis. Some minor, late-stage epidote, laumontite, anhydrite, and calcite in the dikes suggests that these minerals may have formed either during fracturing of the cooling dikes at the time of dike transport, or were part of a feeder system to the overlying basalts.
6. The presently measured temperatures of 195°C at 2000 mbsf indicate that deweylite can form well above its previously estimated crystallization temperature of 50°C.

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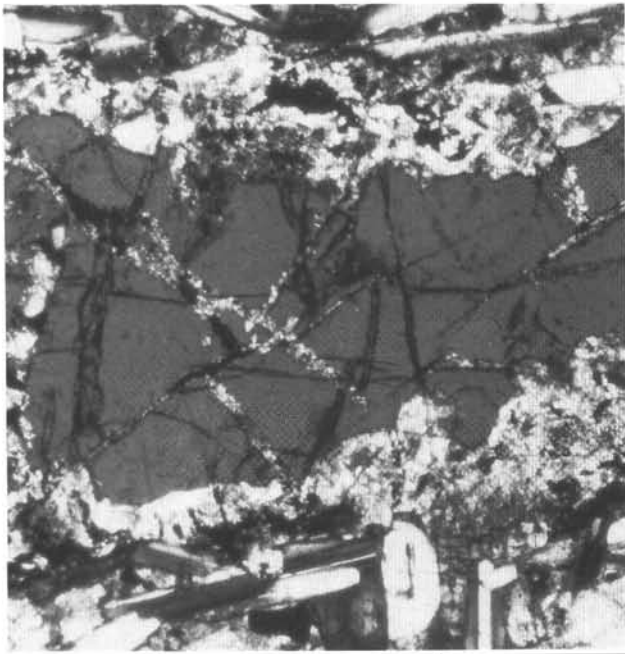
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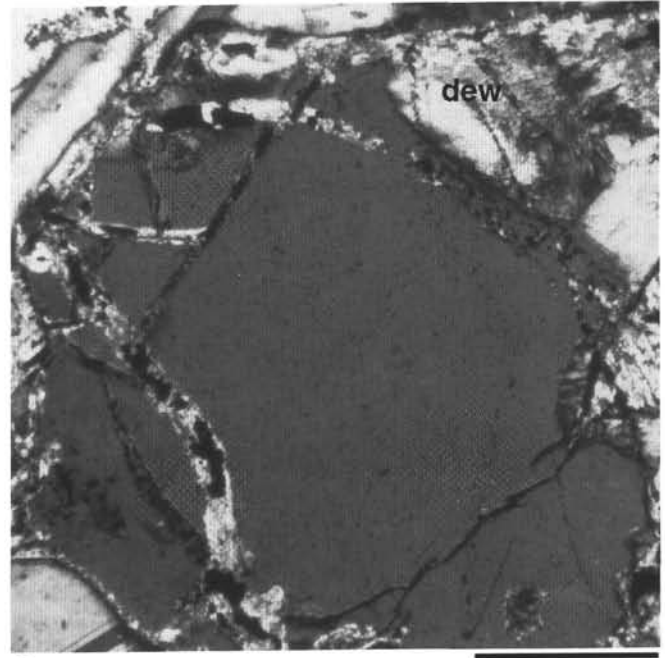
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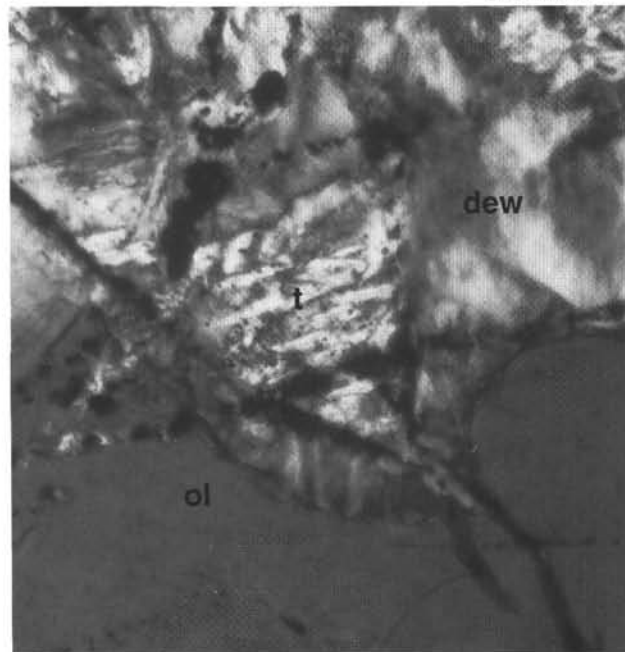
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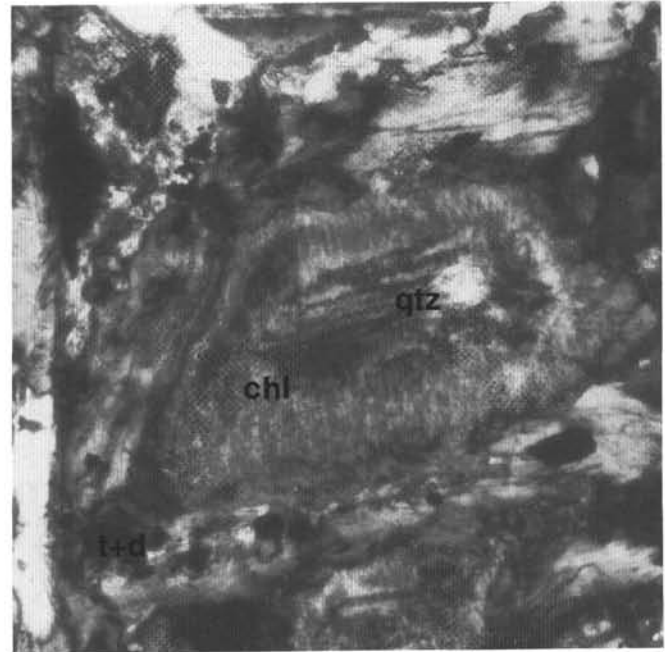
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2 0.5 mm

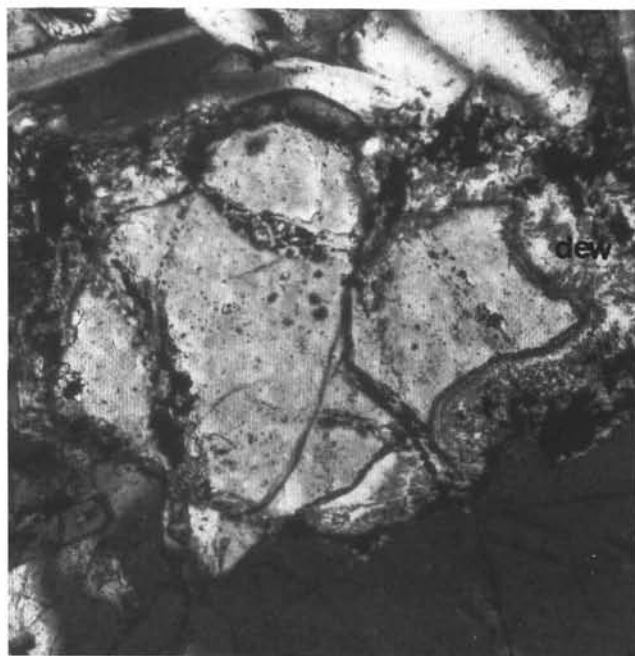


3 0.25 mm



4 0.5 mm

Plate 1. 1. Photomicrograph of olivine phenocryst rimmed by talc \pm magnetite, and fractures are filled by fine-grained magnetite. Sample 140-504B-200R-1, 83–85 cm. Scale bar = 0.5 mm. 2. Photomicrograph of olivine phenocryst rimmed by talc, and fracture is filled by talc + magnetite with some deweylite (dew). Sample 140-504B-200R-1, 83–85 cm. Bar = 0.5 mm. 3. Photomicrograph of talc aggregate (t) included in deweylite (dew), which replaces talc on olivine (ol) rim. Sample 140-504B-200R-1, 130–132 cm. Bar = 0.25 mm. 4. Photomicrograph of olivine rimmed by talc and deweylite (t+d), and center is replaced by chlorite (chl). One subrounded quartz grain (qtz) is located in chloritized center. Sample 140-504B-237R-1, 3–5 cm. Bar = 0.5 mm.



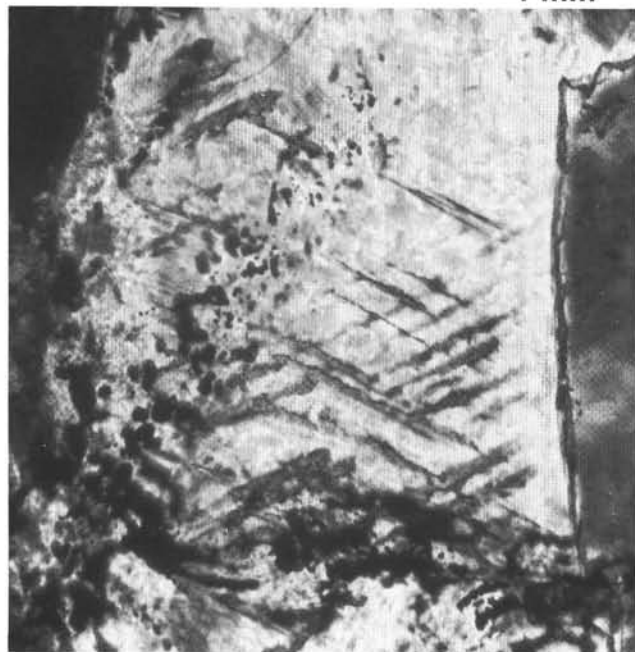
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1 mm



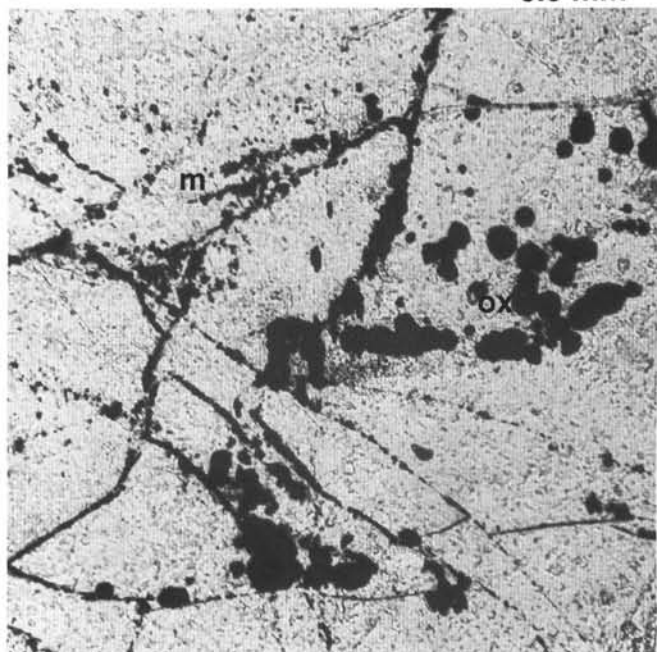
2

0.5 mm



3

0.5 mm



4

0.5 mm

Plate 2. 1. Photomicrograph of olivine phenocryst rimmed by talc (t). Deweylite (dew) partly replaces talc. Note "swollen" texture of deweylite compared to talc. Sample 140-504B-200R-1, 130-132 cm. Bar = 1 mm. 2. Photomicrograph of olivine completely replaced by deweylite. Deweylite shows mesh rims, a texture typically found in serpentine. Sample 140-504B-208R-1, 0-3 cm. Bar = 0.5 mm. 3. Photomicrograph of inter-penetrating texture (typical serpentine texture) of deweylite altered olivine. Sample 140-504B-208R-1, 14-16 cm. Bar = 0.5 mm. 4. Photomicrograph of fine-grained, anhedral magnetite (m) and subrounded Fe³⁺-oxide (ox) in talc and deweylite altered olivine. Sample 140-504B-200R-1, 130-132 cm. Bar = 0.5 mm.