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METASOMATIC VEINS AND MINERALS IN MANTLE-DERIVED XENOLITHS, ANTARCTICA

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Abstract: Late Cenozoic basanites of the McMurdo Volcanic Group, Antarctica, contain numerous ultramafic xenoliths derived from the upper mantle. The xenoliths show multiple-episodes of metasomatism resulting in formation of the veined metasomites and the equilibrated metasomites. The metasomatized xenoliths are characterized texturally and chemically by co-existence of Ti-augite, phlogopitic mica, pargasitic and kaersutitic amphiboles, Al-spinel and apatite with the upper mantle olivine, pyroxenes, and Cr-spinel. Ti-, Al-, Fe- and Ca-enrichments and Si-, Cr- and Mg-depletions observed in the metasomatic clinopyroxenes indicate that the metasomatism was probably generated by an alkaline silicate melt reacting with solid phases of the upper mantle. Ti- and Fe-enrichments and Al-depletion in the metasomatic clinopyroxenes can be also detected as a separate episode of metasomatism different from the above veined-type reactions. Texturally and chemically equilibrated phlogopites and pargasites in the mantle-derived xenoliths provide a different type metasomatism, showing conspicuous depletions in TiO_2, Al_2O_3, Cr_2O_3, and K_2O, and enrichments in SiO_2 and Na_2O.

1. Introduction

Recent studies of ultramafic xenoliths derived from the upper mantle have provided much information on petrographic and geochemical evidence for mantle metasomatism (for example; GRIFFIN, 1973; FREY and GREEN, 1974; HARTE *et al.*, 1975; FRANCIS, 1976; BESWICK and CARMICHAEL, 1978; FREY and PRINZ, 1978; BOETTCHER *et al.*, 1979; MENZIES and MURTHY, 1980; WILSHIRE *et al.*, 1980; IRVING, 1980; BOETTCHER and O'NEIL, 1980; BERGMAN, *et al.*, 1981; BAILEY, 1982; MENZIES and WASS, 1983; HAGGERTY, 1983; WEDEPOHL *et al.*, 1984; DAWSON, 1984, 1987; KEMPTON, 1987; LLOYD, 1987; HARTE *et al.*, 1987; ERLANK *et al.*, 1987; NIELSON and NOLLER, 1987). Modeling for such a metasomatic process has also attempted (for example, FREY and PRINZ, 1978; MENZIES, 1983; FREY, 1984; MENZIES *et al.*, 1987; WILSHIRE, 1987). Nevertheless, the metasomatic process has been essentially unconstrained and the metasomatic agent has not been specified (EGGLER, 1987).

Late Cenozoic basanites of the McMurdo Volcanic Group (KYLE and COLE, 1974) on the western margin of the Ross Sea, Antarctica, carry a large number of xenoliths from the upper mantle (PRIOR, 1907; THOMSON, 1916; FORBES, 1963; FORBES and BANNO, 1966; COLE *et al.*, 1971; STUCKLESS and ERICKSEN, 1976; KYLE *et al.*, 1987). Some xenoliths contain metasomatic veins and minerals, which are considered to have been produced predominantly by a metasomatic reaction between xenoliths and the host basanite magma.

This paper describes the mode of occurrence of some metasomatic veins and minerals and reports the mineral chemistry including the metasomatic changes in chemical composition.

2. Samples Examined

A large number of ultramafic to mafic xenoliths are observed in the basanitic lava flows and in the scoria cone deposits of the Late Cenozoic McMurdo Volcanic Group, Antarctica (KYLE *et al.*, 1987). The xenolith samples examined in this paper were collected at the following points in the McMurdo Sound region (Fig. 1).

Turtle Rock (77°44′S, 166°48′E): Turtle Rock appears to be a remnant of the basanitoid scoria cone about 1 km off the western coast of the Hut Point Peninsula. Xenoliths contained in the scoria cone deposits are classified into the two series as follows; (1) dunite-wehrlite-clinopyroxenite-gabbro as a cumulate series and (2) dunite-lherzolite-clinopyroxenite xenoliths derived from the upper mantle (NIIDA *et al.*, 1986). All of the mantle-derived xenoliths are recognized as the spinel- and the plagioclase-lherzolite facies. No garnet lherzolite has been found from Turtle Rock. Metasomatic veins and veinlets are observed in some xenoliths derived from the upper mantle (Sample No. 73-2). In this paper, the Turtle Rock clinopyroxene attaining an average compo-

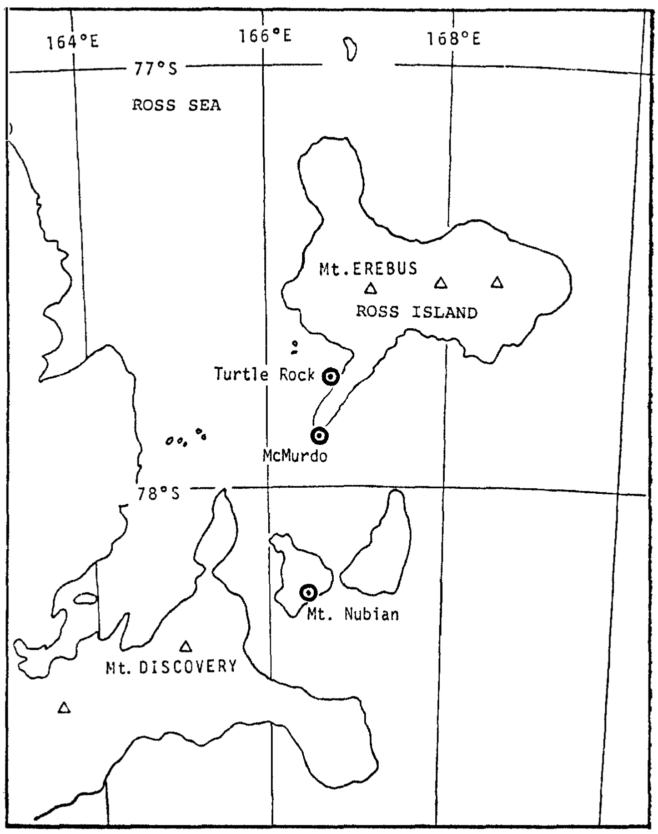


Fig. 1. Locations of sampling site for the metasomatized xenoliths derived from the upper mantle.

sition in major elements was used as a representative of the upper mantle clinopyroxenes for normalization.

McMurdo Station (77°51′S, 166°40′E): The basanitoid lava flows and the scoria cones around McMurdo Station carry numerous xenoliths from the upper mantle, as already reported by PRIOR (1907), THOMSON (1916), FORBES (1963), COLE *et al.* (1971), KYLE *et al.* (1987). There is a wide variety of xenolith types from ultramafic to mafic in composition. Most of the xenoliths from the basanitoid lava flow beside the Helo Pad of McMurdo Station are characterized by a common feature of penetration of reaction veins and veinlets, suggesting an evident metasomatism (Sample Nos. RS3-1 and RS3-4).

Mt. Nubian (78°15′S, 166°24′E): Ultramafic to mafic xenoliths are also included in the scoriaceous cone deposits distributed around the summit of Mt. Nubian, Black Island (COLE and EWART, 1968). Xenolith type includes the cumulate series rocks and the mantle-derived periodotites and clinopyroxenites. Phlogopites and pargasites are rarely found in the mantle-derived xenoliths (Sample No. 113-A2) and also in the cumulative ones (Sample No. 113-B6).

3. Types of Metasomatized Xenolith

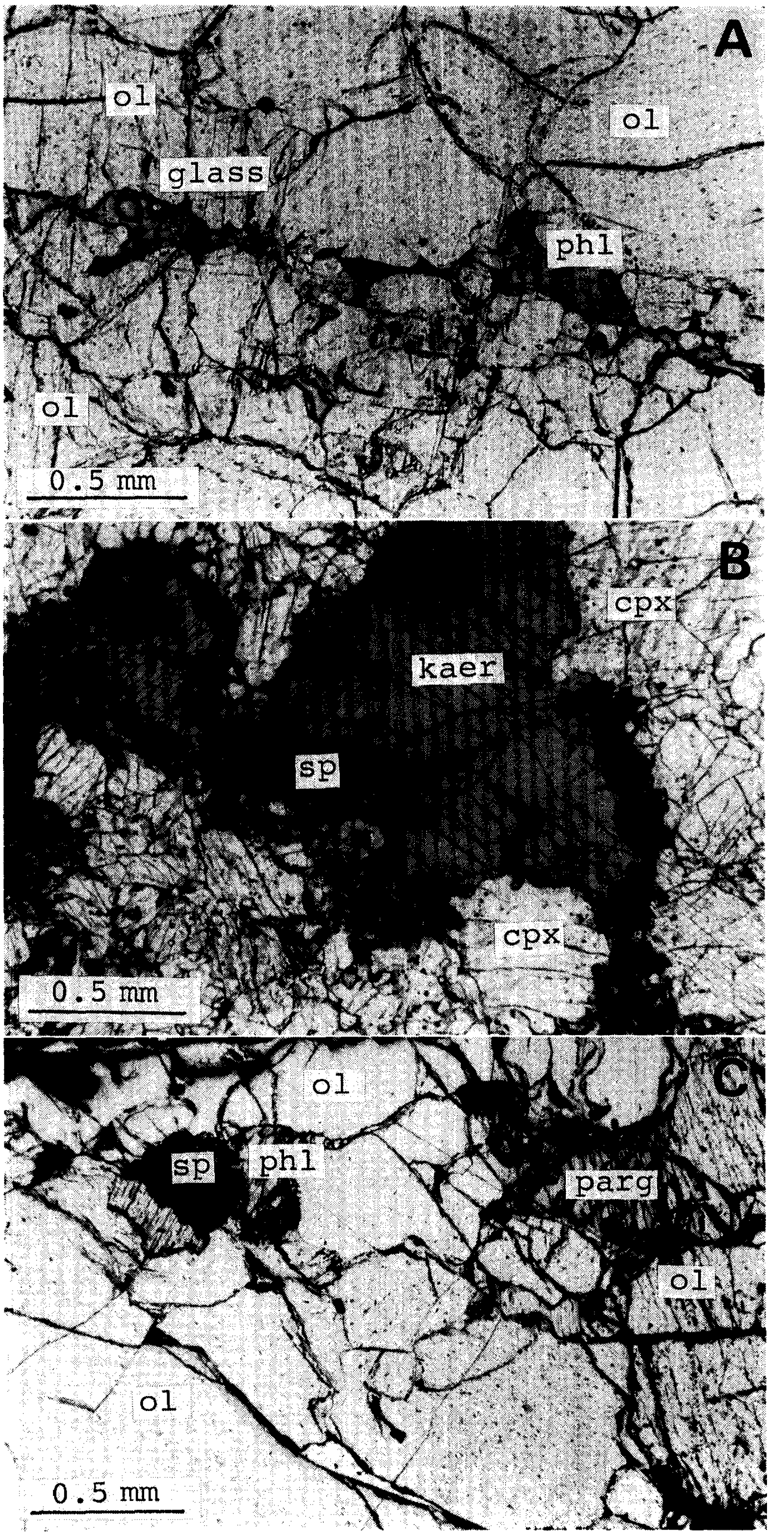
Metasomatized xenoliths and the metasomatic features can be classified into the following three types on their textural and modal grounds:

1) Glass-bearing veined type metasomite (Samples; 73-2, RS3-1)
2) Crystalline veined type metasomite (Sample; RS3-4)
3) Equilibrated type metasomite (Samples; 113-A2, 113-B6)

Titaniferous and hydrous minerals such as kaersutite and phlogopite are often found in the metasomatic veins and veinlets crosscutting the mantle-derived xenoliths. In frequent cases, quenching glasses are observed in association with the hydrous minerals (Fig. 2A). Olivines and Ti-augites crystallized from the silicate melt are commonly plentiful in the quenched glass-bearing veins. Metasomatic reactions, which appear to have taken place between the solid phases of the xenoliths and the silicate melt, can be traced along the veins and veinlets.

Quenched glass-free metasomatic reaction veins and veinlets composed completely of crystalline phases are also found (Fig. 2B). The metasomatic phases include phlogopite, kaersutite, Ti-augite, green Al-spinel and apatite. The lithology characterized by existence of the above phases indicates a conspicuous enrichment of Ti, Al, Fe, Ca and P within the veins and veinlets. Occurrence of Al-spinels is the most abundant on the border in contact with plagioclases.

Discrete grains of phlogopites and pargasites are also found in the mantle-derived xenoliths (Fig. 2C). The discrete hydrous minerals are texturally equilibrated with the surrounding olivine, clinopyroxene, orthopyroxene and spinel. With a few exceptions most of the hydrous minerals are unzoned in composition and appear to have been formed by the different metasomatic events from those for the above types 1) and 2).



A: Glass-bearing metasomatic veinlet in dunite xenolith (Sample No. RS3-1). Quenched glass contains microlites and vesicles in association with phlogopites.

B: Metasomatic kaersutites in the crystalline reaction vein observed in plagioclase clinopyroxenite xenolith (Sample No. RS3-4). Zoned clinopyroxenes change the composition Ti- and Al-rich toward the reaction vein.

C: Phlogopite and pargasite showing an equilibrated texture with the surrounding olivines, contained in dunite xenolith (Sample No. 113-A2).

Fig. 2. Photomicrographs showing textural relationships, all in plane-polarized light. Legend for this figures is as follows: ol, olivine; cpx, clinopyroxene; sp, spinel; parg, pargasite; kaer, kaersutite; phl, phlogopite; glass, quenched basanitoid.

4. Chemistry of Metasomatic Minerals

4.1. Clinopyroxenes

Chemical composition of metasomatic clinopyroxenes shows a wide range in major elements. Table 1 lists the selected EPMA analyses for the clinopyroxenes.

The mg value (mg = 100 Mg/Mg + Fe) for the clinopyroxenes from the mantle-derived xenoliths (Sample No. 73-5), which are considered to be a representative of the upper mantle, ranges from 88.4 to 91.3. The clinopyroxenes from the cumulate series xenoliths show a rather wide range in mg from 70.1 to 79.2. As clearly shown in Fig. 3, metasomatic clinopyroxenes occupy the gap of mg values (79.2 to 88.4) between the cumulate and the upper mantle clinopyroxenes.

Figure 3 shows that the Cr_2O_3, TiO_2, Al_2O_3 and Na_2O contents for the clinopyroxenes from the types 1) and 2) veined metasomites and from the type 3) equilibrated metasomites fall into the separate fields. The types 1) and 2) clinopyroxenes analyzed are from the core off the reaction border of veins and veinlets in the metasomites. Additionally, it is obvious that the fields shift from the primary compositional range

Table 1. Representative microprobe analyses for clinopyroxenes.

Specimen Type	73-5 L	73-2 L		73-2 HB	RS 3-4 CPX		RS 3-4 CPX		113-B6 OCPX	
Analysis No.	core 103	core 15	rim 16	g.m. 27	core 2	rim 4	core 43	rim 44	core 42	core 48
SiO_2	51.64	51.93	48.68	44.50	51.48	45.57	51.84	44.91	53.65	53.55
TiO_2	0.41	0.66	2.22	3.37	0.77	2.09	0.68	2.95	0.15	0.09
Al_2O_3	5.09	3.74	5.35	9.88	3.32	9.96	3.47	9.65	0.88	0.51
Cr_2O_3	1.02	1.36	0.56	0.24	0.29	0.04	0.34	0.12	0.33	0.25
FeO*	3.43	3.79	4.99	7.21	4.37	6.25	4.91	7.81	3.79	3.99
MnO	0.14	0.12	0.10	0.17	0.14	0.14	0.08	0.07	0.15	0.11
MgO	16.98	17.47	14.43	12.47	15.49	12.23	15.17	11.66	16.11	16.25
CaO	21.09	21.06	22.89	21.44	23.16	22.89	23.09	22.46	24.36	24.68
Na_2O	0.94	0.48	0.38	0.72	0.69	0.82	0.68	0.88	0.90	0.93
Total	100.74	100.61	99.60	100.00	99.71	99.99	100.26	100.51	100.32	100.36
Numbers of cations on the basis of 6 oxygens										
Si	1.866	1.882	1.806	1.664	1.898	1.700	1.903	1.680	1.965	1.963
Al^{IV}	0.134	0.118	0.194	0.336	0.102	0.300	0.097	0.320	0.035	0.022
Al^{VI}	0.083	0.042	0.040	0.099	0.042	0.138	0.053	0.106	0.003	—
Ti	0.011	0.018	0.062	0.095	0.021	0.053	0.019	0.083	0.004	0.003
Cr	0.029	0.039	0.016	0.007	0.009	0.001	0.010	0.004	0.010	0.007
Fe	0.104	0.115	0.115	0.225	0.135	0.195	0.151	0.245	0.116	0.123
Mn	0.004	0.004	0.003	0.005	0.004	0.004	0.003	0.002	0.005	0.003
Mg	0.915	0.944	0.799	0.695	0.852	0.680	0.830	0.650	0.880	0.888
Ca	0.816	0.818	0.910	0.859	0.915	0.915	0.908	0.901	0.956	0.969
Na	0.066	0.034	0.028	0.052	0.049	0.059	0.049	0.064	0.064	0.066
mg**	89.8	89.2	83.8	75.5	86.3	77.7	84.6	72.6	88.3	87.9

* Total iron as FeO, ** mg = 100 Mg/Mg + Fe.
Rock type: L, lherzolite; HB, host basanitoid; CPX, clinopyroxenite; OCPX, olivine clinopyroxenite.

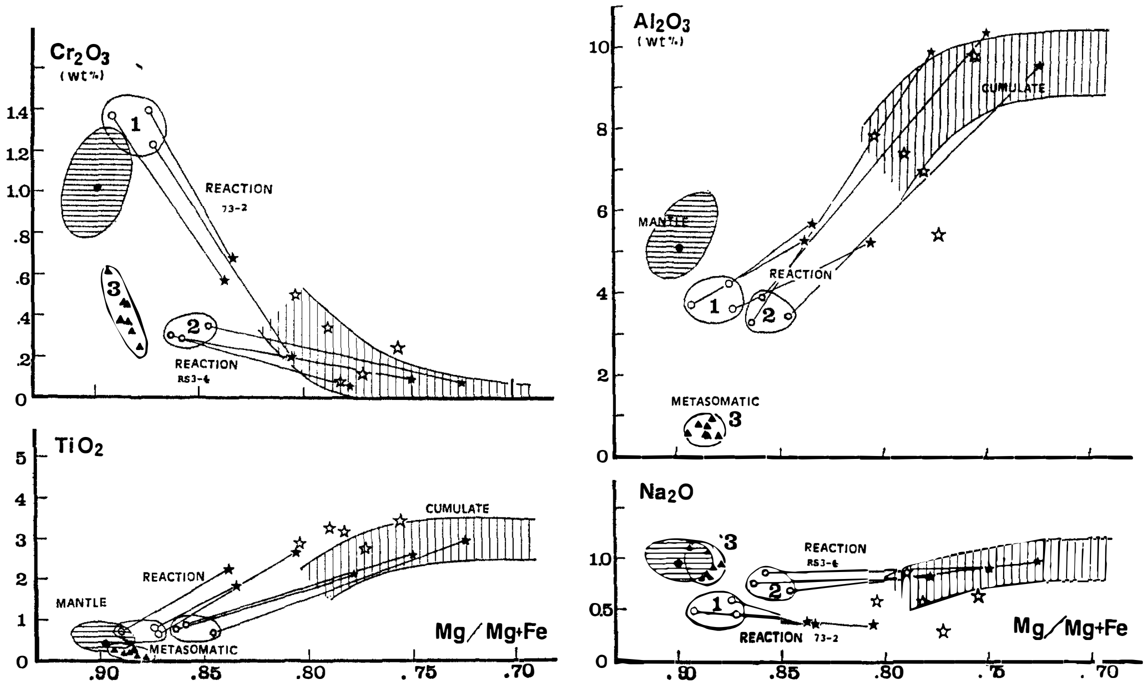


Fig. 3. Compositional variations in Cr_2O_3, TiO_2, Al_2O_3, and Na_2O contents versus Mg/Mg+Fe for clinopyroxenes. Areas enclosed in solid line are for clinopyroxenes; (1) from the lherzolite (Sample No. 73-2), (2) from the plagioclase clinopyroxenite (Sample No. RS3-4), and (3) from the pargasite- and phlogopite-bearing dunite (Sample No. 113-A2). Zoned clinopyroxenes tied from the core (open circles) toward the rim in contact with the vein (solid stars) show reaction relationships in composition detected from the veined metasomites (Sample Nos. 73-2 and RS3-4). Compositional ranges shown by vertically shaded zones are from the cumulate series (unpublished data). Open stars represent the groundmass clinopyroxenes in host basanitoids. Solid circle in horizontally shaded area of the mantle clinopyroxenes (Turtle Rock lherzolite; No. 73-5) is used as a representative composition of the upper mantle clinopyroxenes for normalization of Fig. 4.

for the upper mantle clinopyroxenes, although the Cr_2O_3 and TiO_2 contents for the type 1) clinopyroxenes slightly overlap with those for the primary ones. This indicates that the chemistry of clinopyroxenes from the outside of veins and veinlets might have been reset to the present compositions before the metasomatic veining and that two events of metasomatism can be detected. Compositional relationship of reactions between the metasomatic agents throughout the veins and the solid mantle metasomatized by the former event is also shown in Fig. 3. Solid star symbols tied from the open circles in Fig. 3 show the compositional range of zoning in clinopyroxenes from the core to the metasomatized rim that is in contact with the vein. They are plotted into the FeO-, TiO_2- and Al_2O_3-rich and Cr_2O_3-poor fields close to those for groundmass clinopyroxenes of the host basanite and for the cumulate series clinopyroxenes.

Ti-, Al-, Fe- and Ca-enrichments and Si-, Cr- and Mg-depletions in the metasomatic clinopyroxenes can be clearly detected by major elements normalization (Fig. 4). The clinopyroxene rims are in contact with the metasomatic veins. Accordingly, the metasomatism is most likely to have been generated by reactions during veining into

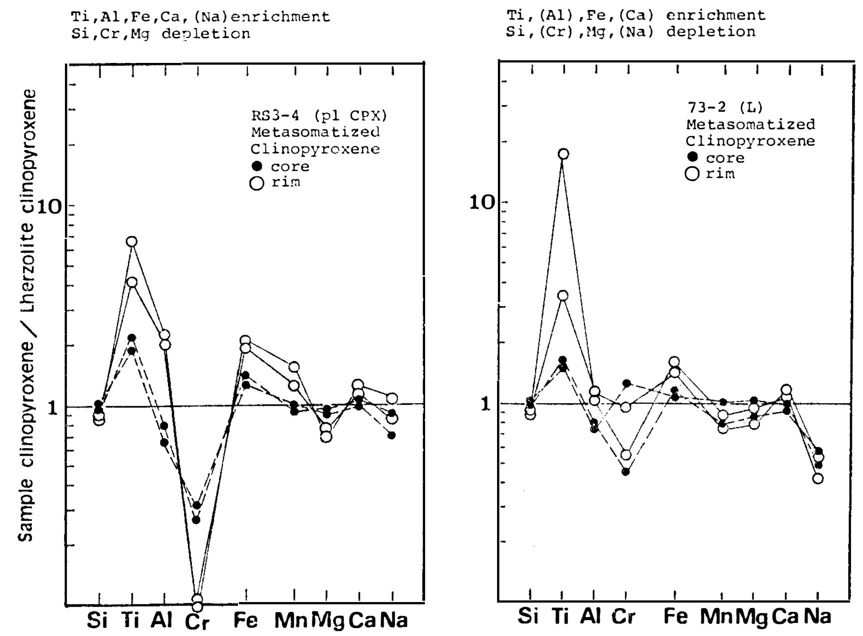


Fig. 4. Major-element composition of zoned clinopyroxenes from the plagioclase clinopyroxenite (Sample No. RS3-4) and the lherzolite (Sample No. 73-2) compared with that of primary clinopyroxene from the Turtle Rock lherzolite (Sample No. 73-5). Solid circles from rims in contact with the metasomatic veins.

the xenoliths. The clinopyroxene cores do not provide the same enrichment and depletion sense to the above metasomatic veining. The normalized values of Al in the core clinopyroxene are rather low. Figure 4 also emphasizes that the metasomatism deduced from the clinopyroxene cores is characterized by an apparent enrichment in Ti and Fe and depletion in Al, Mg and Na.

Metasomatic enrichment in Ti and Fe is believed to be in consensus as a general tendency. Al-depletions during metasomatism, however, have been scarcely known in the clinopyroxenes from the South West Ugandan xenoliths (LLOYD, 1987) and from the Kimberley (ERLANK *et al.*, 1987).

4.2. Pargasites and kaersutites

The selected EPMA analyses for pargasitic and kaersutitic amphiboles from the metasomatized dunite (Sample No. 113-A2) and from the metasomatic veins and veinlets in the dunite xenolith (Sample No. RS3-1) and in the plagioclase clinopyroxenite (Sample No. RS3-4) are listed in Table 2.

The mg value (mg = 100 Mg/Mg + Fe) for pargasitic amphiboles of the pargasite-bearing phlogopite dunite ranges from 89.3 to 90.0. The kaersutitic amphiboles in the metasomatic veins have a wide range of mg from 64.5 to 75.4.

The TiO_2 contents in amphiboles (Fig. 5) show a clear contrast between the equilibrated type 3) metasomites and the veined types 1) and 2). The type 3) dunite is characterized by coexistence with TiO_2-poor pargasites, whereas the types 1) and 2) veined metasomites contain TiO_2-rich pargasites and kaersutites.

As shown in Fig. 5, the range of TiO_2 contents and mg values for the veined type

Table 2. Representative microprobe analyses for pargasitic and kaersutitic amphiboles and phlogopitic micas.

Specimen Type	113-A2 PHLD	RS 3-1 VEIN		RS 3-4 VEIN			113-A2 PHLD	113-B6 OCPX	RS 3-1 VEIN
Mineral No.	parg 23	Kaer 135	Kaer 137	Ti-parg 2	Kaer 30	Kaer 56	phl 8	phl 36	phl 73
SiO_2	43.04	39.24	36.91	39.57	39.21	37.39	39.78	40.02	35.73
TiO_2	1.13	6.09	6.70	4.19	5.80	6.07	0.86	1.70	3.98
Al_2O_3	12.14	13.13	14.14	15.67	14.91	14.65	15.68	13.43	16.80
Cr_2O_3	1.99	0.08	0.02	0.01	0.09	0.08	1.31	0.70	2.13
FeO*	3.90	8.92	10.06	8.15	9.61	11.09	3.46	6.73	4.58
MnO	0.00	0.11	0.09	0.07	0.13	0.23	0.08	0.10	0.04
MgO	18.63	13.97	12.71	14.01	12.30	11.29	24.41	23.04	19.66
CaO	12.24	12.17	11.76	11.88	11.69	12.23	0.01	0.05	0.19
Na_2O	3.77	2.63	2.87	2.63	2.66	2.74	1.83	1.46	2.74
K_2O	0.56	1.26	1.55	1.25	1.20	1.35	8.04	8.83	9.51
Total	97.40	97.60	96.81	97.43	97.60	97.12	95.46	96.06	95.36
	23(0)	23(0)	23(0)	23(0)	23(0)	23(0)	22(0)	22(0)	22(0)
Si	6.192	5.796	5.558	5.798	5.783	5.627	5.587	5.703	5.180
Al^{IV}	1.808	2.204	2.442	2.202	2.217	2.373	2.413	2.256	2.850
Al^{VI}	0.251	0.083	0.068	0.504	0.374	0.225	0.183	—	0.050
Ti	0.122	0.676	0.759	0.461	0.643	0.687	0.091	0.199	0.434
Cr	0.226	0.010	0.002	0.001	0.011	0.010	0.145	0.079	0.243
Fe	0.469	1.102	1.266	0.999	1.185	1.396	0.406	0.802	0.579
Mn	0.000	0.013	0.012	0.009	0.017	0.030	0.011	0.013	0.005
Mg	3.995	3.075	2.855	3.059	2.704	2.533	5.112	4.894	4.248
Ca	1.886	1.926	1.898	1.868	1.847	1.972	0.001	0.009	0.029
Na	1.051	0.751	0.838	0.748	0.761	0.798	0.498	0.422	0.772
K	0.102	0.237	0.298	0.234	0.226	0.260	1.504	1.606	1.759
mg**	89.5	73.6	69.2	75.4	69.5	64.5	92.6	85.9	88.5

* Total iron as FeO, ** mg=100 Mg/Mg+Fe.

amphiboles overlaps with the TiO_2- and FeO-rich kaersutitic amphiboles from the cumulate series xenoliths. On the other hand, the equilibrated type pargasitic amphiboles are characterized by the low contents of Cr_2O_3, Al_2O_3, and K_2O as well as TiO_2 and also by the high contents of SiO_2 and Na_2O. Such a compositional contrast on metasomites between the equilibrated type and the veined type has been emphasized by WILSHIRE *et al.* (1980) and WILKINSON and LE MAITRE (1987).

4.3. Phlogopites

The selected EPMA analyses for phlogopitic micas from the metasomatic types 1) and 3) are listed in Table 2.

The mg value (mg = 100 Mg/Mg + Fe) of the phlogopitic micas from the equilibrated metasomites ranges from 91.5 to 92.6 for the pargasite-bearing phlogopite dunite (Sample No. 113-A2) and from 85.8 to 86.9 for the phlogopite clinopyroxenite (Sample No. 113-B6). The mg value of the veined micas in the type 1) metasomite (Sample No. RS3-1) ranges from 86.4 to 88.5.

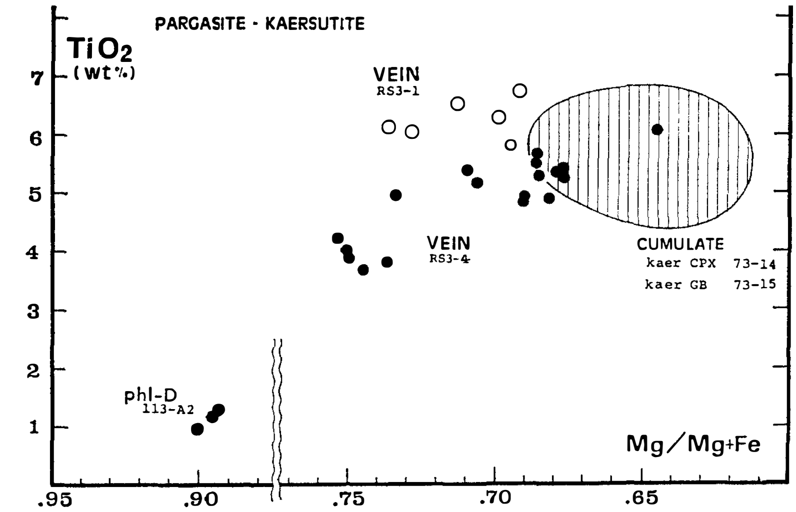


Fig. 5. Compositional variations in TiO_2 versus $Mg/Mg+Fe$ for pargasitic and kaersutitic amphiboles from the veined type metasomites (Sample Nos. RS3-1 and RS3-4) and from the equilibrated type metasomite (Sample No. 113-A2).

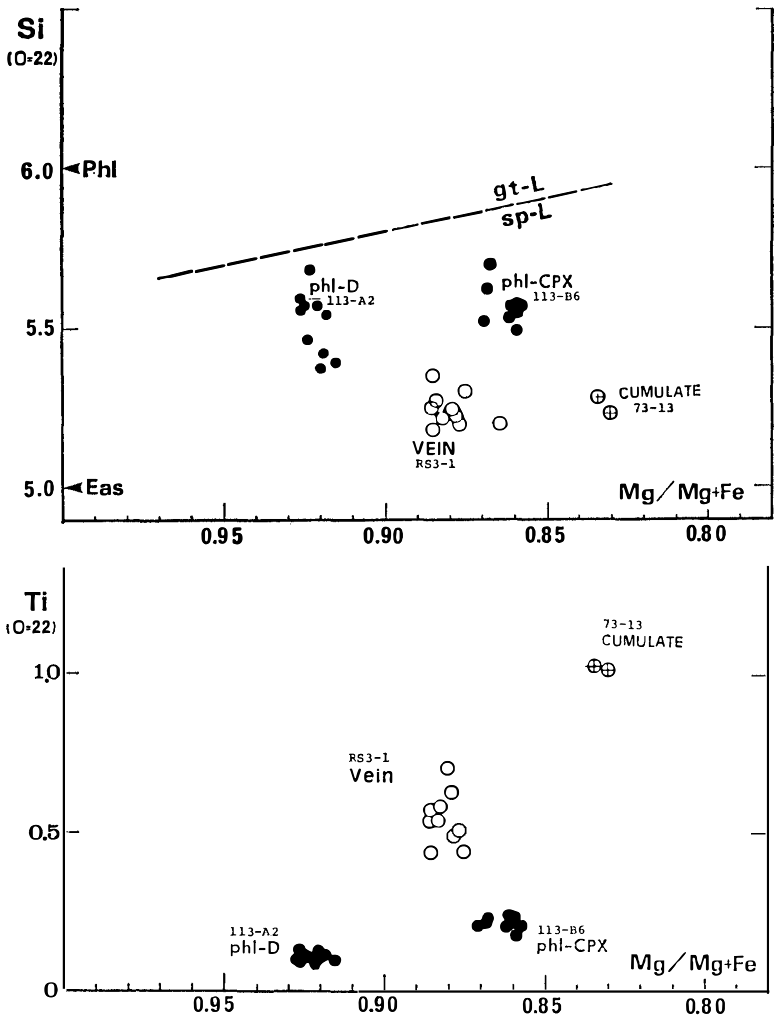


Fig. 6. Compositional variations in Si and Ti versus $Mg/Mg+Fe$ for phlogopitic micas from the veined type metasomite (Sample No. RS 3-1) and the equilibrated type metasomites (Sample Nos. 113-A2 and 113-B6). Boundary between the garnet- and spinel-lherzolites is shown by dashed line (ARAI, 1984).

The phlogopitic micas from the equilibrated type metasomites listed in Table 2 are Si- and Na-rich and Ti-, Al- and K-poor. All of the micas show the similar compositional variations to those from the spinel lherzolite facies xenoliths (ARAI, 1984). As shown in Fig. 6, the veined micas are characterized by a reversed chemical nature rich in Ti, Al and K and poor in Si and Na, compared with the equilibrated type phlogopitic micas.

5. Conclusion

(1) A large number of ultramafic xenoliths derived from the upper mantle are contained in the basanitic lava flows and the scoria cone deposits of the Late Cenozoic McMurdo Volcanic Group. Some reaction veins and minerals in the xenoliths provide multiple-episodes of metasomatism deduced from the mode of occurrence and the chemical characteristics.

(2) Metasomatized xenoliths and the metasomatic features are classified into the following three types on their textural and chemical grounds; 1) glass-bearing veined type, 2) crystalline veined type, and 3) equilibrated type.

(3) The veined types 1) and 2) metasomites contain Ti-augites, phlogopitic micas, pargasitic and kaersutitic amphiboles, Al-spinels and apatites in the reaction veins and veinlets, most of which are considered to have resulted in introducing Ti, Al, Fe, K and P elements of highly alkaline silicate melt into the mantle-derived xenoliths.

(4) Zoned clinopyroxenes in contact with the metasomatic veins and veinlets show conspicuous enrichments in Ti, Al, Fe and Ca and depletions in Si, Cr and Mg. This indicates that the metasomatism was probably generated by reaction of an alkaline silicate melt with the solid phases of the upper mantle during the veining recognized in the metasomatized xenoliths.

(5) Ti- and Fe-enrichments and Al-depletions are also conspicuous in the metasomatic clinopyroxene cores outside of veins and veinlets in the veined types 1) and 2) metasomites. Compared with the above intra-veined type metasomatism, a different metasomatism can be detected as a separate episode which occurred at the later stage.

(6) The equilibrated type 3) metasomites are characterized by co-existence of hydrous minerals such as phlogopites and pargasites. The hydrous minerals are poor in TiO_2, Al_2O_3, Cr_2O_3, and K_2O and rich in SiO_2 and Na_2O. Accordingly, it is considered that the metasomatism recognized in the equilibrated type is different from that of the above both veined types. The metasomatic agent, however, has not been specified.

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