CUMULATE INCLUSIONS FROM TURTLE ROCK, ROSS ISLAND, ANTARCTICA

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Abstract: Ultramafic to mafic cumulate inclusions in Late Cenozoic basanite at Turtle Rock off Ross Island, Antarctica, were used to propose a well-defined compositional variation of the constituent minerals. The Turtle Rock cumulate suite (dunite-wehrlite-clinopyroxenite-gabbro), composed of Fe-rich olivine, clinopyroxene, kaersutitic amphibole, plagioclase and Ti-Fe oxide minerals, has undeformed and unmetasomatized igneous cumulate textures.

All the ferromagnesian minerals are Fe-rich ($100Mg/(Mg + Fe) = 87–60$). Clinopyroxenes are dominant in the cumulates and are always Fe-, Ti-, and Al-rich fassaitic augites, of which compositional range is separated from that of the upper mantle clinopyroxenes. Kaersutitic amphibole, varying continuously from Ti-pargasite to kaersutite, has a chemical composition typical of amphibole found in subcontinental cumulate xenoliths.

1. Introduction

Two common types of mantle-derived ultramafic xenoliths have been identified within alkaline basalts in continental areas (for example, IRVING, 1974, 1980; WILSHIRE and SHERVAIS, 1975; FREY and PRINZ, 1978). Ultramafic xenoliths found in the Newer Basalts of Victoria, Australia, were divided into olivine-rich lherzolite suite and Al-pyroxene-rich suite (IRVING, 1974), and those in basalts from the western United States into Cr-diopside group and Al-augite group (WILSHIRE and SHERVAIS, 1975). The olivine-rich lherzolite suite is characterized by "green-pyroxene" (Cr-diopside) and Mg-rich olivine, whereas the Al-pyroxene-rich suite contains "black-pyroxene" (Al-augite) and Fe-rich olivine. WILSHIRE and SHERVAIS (1975) emphasized that within the latter group igneous structures and textures are well preserved. These suites were designated as Group I and Group II, respectively, by FREY and PRINZ (1978). Group I xenoliths from San Carlos, Arizona, are dominated by magnesian peridotites containing Cr- and Mg-rich minerals ($mg\# = 100Mg/(Mg + Fe) > 85$), whereas Group II xenoliths are dominated by clinopyroxene-rich peridotites and pyroxenites containing Al-, Ti- and Fe-rich minerals ($mg\# < 85$). The origin of both types has been discussed by many workers, with a possible consensus that the Group II is a cumulate derived from a SiO_2-undersaturated magma. Some varieties of Group II xenoliths, however, have been shown to be upper mantle fragments modified by metasomatism (LLOYD, 1987).

Late Cenozoic basanites of the McMurdo Volcanic Group (KYLE and COLE, 1974) on the western margin of the Ross Sea, Antarctica, are host to a large number of

xenoliths from the upper mantle (KYLE *et al.*, 1987). Sampling for ultramafic to mafic xenoliths was done twice at Turtle Rock, Ross Island, by the authors during the 1984–1985 field season, and provided a wide variety of cumulates, involving dunite, wehrlite, clinopyroxenite, and gabbro. This paper presents the petrography and mineral chemistry of the cumulate suite inclusions.

2. Cumulate Inclusions Examined

Turtle Rock is located at 77°44′S, 166°48′E, approximately 1 km off the western coast of the Hut Point Peninsula, Ross Island, Antarctica (Fig. 1). The exposed area of the Turtle Rock island above sea level appears to be a remnant of a basanitoid scoria cone, including a large number of ultramafic to mafic cumulates and mantle-derived xenoliths (NIIDA, 1988, 1990).

Of the 117 xenolith samples collected from Turtle Rock, approximately 80% are of cumulate origin. The remaining 20% include spinel dunite, harzburgite and lherzolite xenoliths derived from solid mantle.

The cumulates, composed essentially of olivine, clinopyroxene, kaersutite, plagioclase and Ti-Fe oxide minerals, are classified into the following rock types on the basis of the IUGS's modal classification (STRECKEISEN, 1973) for plutonic rocks: dunite (Sample No. 73-21), wehrlite (Nos. 1213-73A and 73-12), kaersutite clinopyroxene wehrlite (No. 73-7C), olivine clinopyroxenite (No. 73-13), olivine kaersutite clinopyroxe-
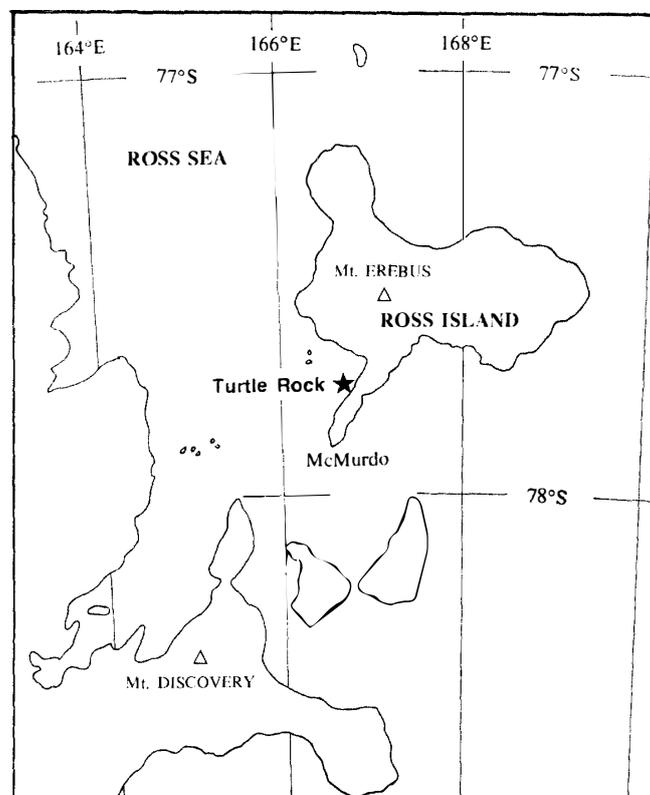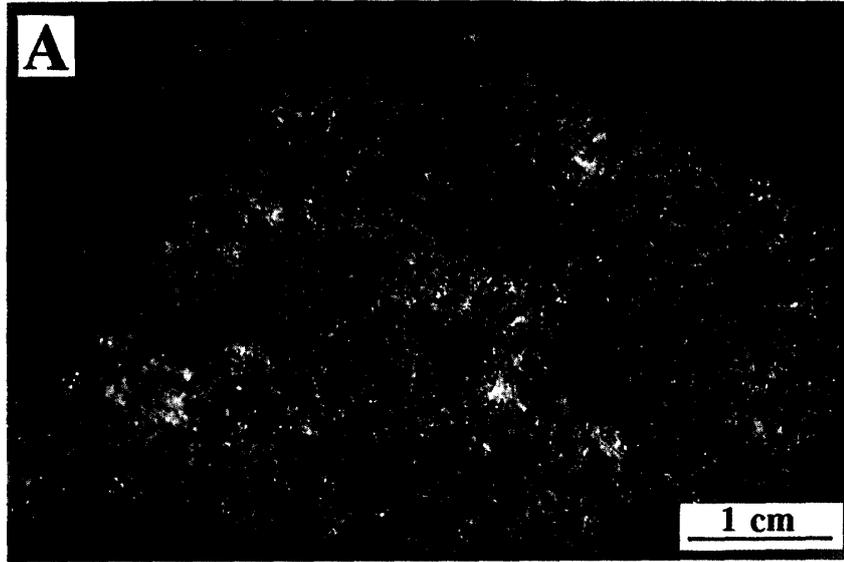

Fig. 1. Location of the Turtle Rock sampling site for the cumulate inclusions.

Fig. 2.   Triangular diagrams of clinopyroxene-kaersutite-olivine (center), plagioclase-kaersutite-clinopyroxene (left), and oxide mineral-clinopyroxene plus kaersutite-olivine (right), showing a wide variation in modal composition for the Turtle Rock cumulates.
Ol: olivine, Cpx: clinopyroxene, Kaer: kaersutite, Pl: plagioclase, OM: oxide minerals.
D: dunite, W: wehrlite, C: clinopyroxenite, K: kaersutitite, GB: gabbro, A: anorthosite.

nite (Nos. 73-6 and 73-23), kaersutite clinopyroxenite (Nos. 1213-73B and 73-14), clinopyroxenite (No. 73-9), kaersutitite (No. 73-7A), olivine gabbro (No. 1219-76A), clinopyroxene kaersutite gabbro (Nos. 73-11 and 73-24a), and kaersutite gabbro (No. 73-15). A small amount of plagioclase is present in some wehrlitic and clinopyroxenitic cumulates, which are designated as plagioclase-bearing wehrlite (No. 73-16a) or plagioclase-bearing clinopyroxenite in this paper.

Figure 2 clearly shows that the cumulates cover a wide range in modal composition from dunite, through wehrlite, clinopyroxenite, to gabbro. The dunite to wehrlite cumulates are composed mainly of olivine with small amounts of clinopyroxene, kaersutitic amphibole and Ti-Fe oxides. The color of cumulus olivines is characteristically brownish yellow (Fig. 3A), which is easily distinguishable from the "olive-green" of the Mg-rich olivine in mantle-derived peridotite xenoliths. Clinopyroxenes are most abundant in the cumulate suite, displaying a black color on the surface of hand-specimens (Figs. 3 B and 3C). The modal composition of Ti-Fe oxides varies from 1.5 to 17.5%. A trace amount of phlogopites is occasionally found as small crystals in clinopyroxene and kaersutite.

All the Turtle Rock cumulates examined in this paper have essentially undeformed and unmetasomatized "igneous" cumulate textures. The textures observed under the microscope are dominated by adcumulus and heteradcumulus growths of unzoned cumulus crystals.

The dunite (No. 73-21) shows an olivine adcumulate texture, composed mostly of an anhedral-granular olivines, 0.4-8.0 mm in size, with small amounts of intercumulus clinopyroxenes. The wehrlite (No. 73-12) and the kaersutite clinopyroxene wehrlite (No. 73-7C) show an olivine-clinopyroxene adcumulate to heteradcumulate texture with

Fig. 3. Cumulate samples from the basanite scoria cone deposits in Turtle Rock, Hut Point Peninsula, Ross Island.

A : Wehrlite (Sample No. 1213-73A), composed mostly of olivine with minor clinopyroxene. Color of olivine is not "olive-green", but characteristically brownish yellow, due to the low mg#-number.

B: Kaersutite clinopyroxenite (Sample No. 1213-73B), composed of "black" clinopyroxene (titaniferous fassaitic augite) and kaersutitic amphiboles with lustrous cleavage. Left half is the host basanite.

C: Olivine-bearing clinopyroxene kaersutite gabbro (Sample No. 1219-76A), included in the host basanite. Constituent minerals: plagioclase (white), kaersutitic amphibole (black), clinopyroxene (black), and olivine (brownish yellow).
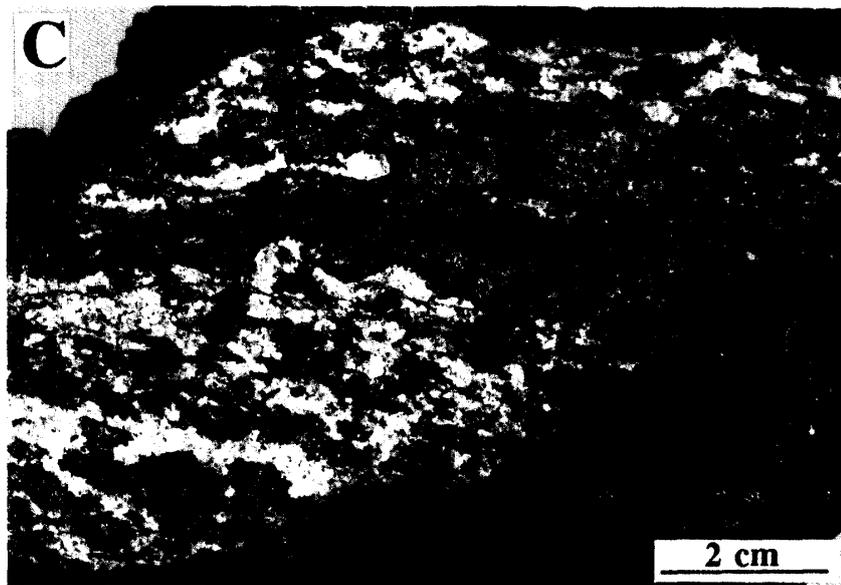
small amounts of euhedral to subhedral cumulus Ti-Fe oxides and intercumulus kaersutites.   The olivine clinopyroxenite (No. 73-13) also shows an clinopyroxene-olivine adcumulate texture, composed of equigranular subhedral to anhedral clinopyroxenes, 0.2-6.0 mm in diameter, and olivines less than 3.5 mm.   The olivine kaersutite clinopyroxenite (No. 73-23) and the kaersutite clinopyroxenite (No. 73-14) are composed mainly of subhedral to anhedral-granular cumulus clinopyroxenes 0.2-8.0 mm in diameter, olivines less than 5.0 mm, and of anhedral cumulus to intercumulus kaersutites less than 13.0 mm, showing an adcumulus to heteradcumulus growth.   A relatively extensive intercumulus overgrowth of kaersutites, including small euhedral grains of cumulus

Table 1.   Representative analyses of olivine, clinopyroxene, kaersutite,

Rock Type	D		W		pl. W				ol. CPX			ol.k.CPX
Sample No.	73-21		73-12		73-16a				73-13			73-23
Mineral Anal. No.	ol 82	cpx 71	ol 5	cpx 79	ol 79	cpx 75	kaer 73	pl 65	ol 35	cpx 37	phl 25	ol 102
SiO₂	40.12	52.19	38.48	45.57	39.10	47.35	39.33	47.47	38.24	45.64	37.36	39.04
TiO₂	—	0.59	—	2.55	—	2.23	5.72	—	—	2.99	9.74	—
Al₂O₃	—	4.13	—	8.77	—	7.59	14.94	33.66	—	9.42	16.27	—
Cr₂O₃	—	0.59	—	0.14	—	0.02	0.05	—	—	0.15	0.19	—
FeO*	15.02	5.01	20.40	6.93	21.32	6.30	8.86	—	20.64	6.90	6.42	22.67
NiO	0.15	—	0.14	—	0.00	—	—	—	0.09	—	0.00	0.10
MnO	0.23	—	0.27	—	0.45	—	0.13	—	0.30	—	0.09	0.33
MgO	45.18	16.57	41.37	12.94	40.60	13.41	13.12	—	41.00	12.72	18.10	39.12
CaO	—	20.57	—	22.41	—	21.30	11.66	16.50	—	21.26	0.11	—
Na₂O	—	0.44	—	0.78	—	1.01	2.82	2.19	—	0.78	0.87	—
K₂O	—	—	—	—	—	—	1.15	0.09	—	—	8.61	—
Total	100.70	100.09	100.66	100.09	101.47	99.21	97.77	99.90	100.27	99.86	97.76	101.26
	O=4	O=6	O=4	O=6	O=4	O=6	O=23	O=8	O=4	O=6	O=22	O=4
Si	1.000	1.902	0.987	1.679	0.997	1.753	5.767	2.177	0.986	1.688	5.225	1.003
Ti	—	0.016	—	0.071	—	0.062	0.631	—	—	0.083	1.025	—
Al	—	0.178	—	0.382	—	0.332	2.589	1.824	—	0.412	2.689	—
Cr	—	0.017	—	0.004	—	0.000	0.006	—	—	0.004	0.021	—
Fe³⁺	—	0.000	—	0.171	—	0.110	—	—	—	0.098	—	—
Fe²⁺	0.313	0.153	0.437	0.043	0.454	0.086	1.087	—	0.445	0.116	0.751	0.487
Ni	0.003	—	0.003	—	0.000	—	—	—	0.002	—	0.000	0.002
Mn	0.005	—	0.006	—	0.010	—	0.016	—	0.007	—	0.011	0.007
Mg	1.678	0.900	1.581	0.711	1.542	0.740	2.868	—	1.575	0.701	3.773	1.498
Ca	—	0.803	—	0.885	—	0.845	1.831	0.811	—	0.842	0.016	—
Na	—	0.031	—	0.056	—	0.072	0.801	0.194	—	0.056	0.235	—
K	—	—	—	—	—	—	0.215	0.005	—	—	1.535	—
Total	2.999	4.000	3.014	4.000	3.003	4.000	15.811	5.011	3.015	4.000	15.281	2.997
mg♯	84.28	85.49	78.33	76.89	77.24	79.12	72.52	—	77.97	76.66	83.40	75.46
cr♯	—	0.09	—	0.01	—	0.00	0.23	—	—	0.01	0.01	—
An	—	—	—	—	—	—	—	80.24	—	—	—	—

FeO*: total iron as FeO*, Fe³⁺: calculated for cpx and oxide minerals, mg♯=100 Mg/(Mg+Fe), cr♯=100 Cr/(Cr+Al),   An: An mol. %, D: dunite, W: wehrlite, CPX: clinopyroxenite, GB: gabbro,

clinopyroxenes and Ti-Fe oxide minerals, is in association with a considerable amount of intercumulus apatites and the Ti-Fe oxides overgrowths. Compositional zoning is hardly observable in each grain of the clinopyroxenite cumulates. The clinopyroxene kaersutite gabbro cumulates (Nos. 73–11 and 73–24a) are composed of subhedral to anhedral grains of cumulus plagioclase, clinopyroxene, Ti-Fe oxides, and subhedral to anhedral columnar grains of kaersutite. The kaersutite gabbro (No. 73–15) is composed mostly of subhedral to anhedral prismatic grains of cumulus plagioclase and kaersutite, up to 8.0 and 13.0 mm in maximum length respectively, showing a characteristic plagioclase-kaersutite adcumulus growth.

plagioclase and oxide minerals from the Turtle Rock cumulates.

ol.k.CPX 73-23		k.CPX 73-14			c.k.GB 73-24a				k.GB 73-15			
cpx 95	kaer 98	cpx 35	kaer 21	o.m. 31	cpx 41	kaer 34	pl 23	o.m. 47	cpx 2	kaer 15	pl 8	o.m. 39
49.23	41.04	44.32	38.12	0.10	46.68	40.04	54.34	0.05	45.14	38.55	53.61	0.00
1.68	5.27	3.15	6.37	15.37	2.45	5.78	—	10.08	2.59	5.85	—	10.10
6.90	13.37	10.07	14.10	9.05	9.26	14.50	29.36	10.83	9.13	14.94	29.42	10.31
0.12	0.21	0.03	0.08	0.44	0.00	0.00	—	0.03	0.00	0.00	—	0.04
7.73	10.00	8.18	10.62	65.94	8.12	11.67	—	72.69	8.42	11.73	—	71.29
—	—	—	—	0.00	—	—	—	0.00	—	—	—	0.00
—	0.11	—	0.09	0.37	—	0.13	—	0.36	—	0.14	—	0.49
13.52	13.46	11.29	12.34	4.80	11.38	11.46	—	3.64	11.62	11.46	—	3.21
20.40	11.32	22.20	11.15	—	20.82	11.29	11.55	—	21.33	11.13	11.35	—
0.92	2.45	1.08	2.74	—	0.95	2.70	4.60	—	0.95	3.06	5.28	—
—	1.16	—	1.20	—	—	1.04	0.30	—	—	1.24	0.28	—
100.49	98.39	100.32	96.81	96.07	99.65	98.61	100.15	97.68	99.18	98.10	99.94	95.44
O=6	O=23	O=6	O=23	O=4	O=6	O=23	O=8	O=4	O=6	O=23	O=8	O=4
1.807	5.985	1.639	5.707	—	1.739	5.873	2.446	—	1.689	5.717	2.425	—
0.046	0.578	0.088	0.717	0.407	0.069	0.638	—	0.262	0.073	0.652	—	0.269
0.299	2.304	0.440	2.495	0.377	0.408	2.514	1.562	0.442	0.404	2.619	1.573	0.432
0.003	0.024	0.001	0.009	0.012	0.000	0.000	—	0.001	0.000	0.000	—	0.001
0.056	—	0.183	—	0.797	0.045	—	—	1.034	0.143	—	—	1.028
0.181	1.220	0.070	1.330	1.144	0.208	1.431	—	1.064	0.121	1.455	—	1.085
—	—	—	—	0.000	—	—	—	0.000	—	—	—	0.000
—	0.014	—	0.011	0.011	—	0.016	—	0.010	—	0.018	—	0.015
0.740	2.926	0.622	2.754	0.252	0.632	2.506	—	0.187	0.648	2.534	—	0.170
0.802	1.769	0.880	1.789	—	0.831	1.774	0.557	—	0.855	1.769	0.550	—
0.065	0.692	0.077	0.795	—	0.069	0.769	0.401	—	0.069	0.880	0.463	—
—	0.216	—	0.229	—	—	0.195	0.017	—	—	0.235	0.016	—
4.000	15.728	4.000	15.836	3.000	4.000	15.716	4.982	3.000	4.000	15.879	5.027	3.000
75.71	70.58	71.09	67.44	18.06	71.41	63.65	—	14.97	71.09	63.53	—	13.53
0.01	1.05	0.00	0.38	3.14	0.00	0.00	—	0.18	0.00	0.00	—	0.25
—	—	—	—	—	—	—	57.10	—	—	—	53.44	—

ol: olivine, cpx(c.): clinopyroxene, kaer(k.): kaersutite, pl: plagioclase, phl: phlogopite, o.m.: oxide mineral.

3. Chemical Composition of Minerals

Constituent minerals in the dunite-wehrlite-clinopyroxenite-gabbro cumulates from Turtle Rock were analyzed with the JEOL JXA733 electronprobe microanalyzer at the National Institute of Polar Research and Hokkaido University, using the standard method of both laboratories. Representative analyses for olivine, clinopyroxene, kaersutitic amphibole, phlogopite, plagioclase and Ti-Fe oxide minerals are listed in Table 1.

3.1. Olivine

The $mg\#$-number ($mg\# = 100\,Mg/(Mg+Fe)$) of olivine from the Turtle Rock cumulates ranges between 83.3–85.4 for dunite, 78.2–79.2 for wehrlite, and 75.2–78.0 for clinopyroxenite. A systematic decrease in $mg\#$ can be traced from dunite to clinopyroxenite (Table 1 and Fig. 4). Although a small amount of olivine is contained in gabbro cumulates, it has not been analyzed.

The MnO content in olivine varies from 0.18 wt% for dunite to 0.37 wt% for clinopyroxenite. As shown in Fig. 4, the MnO content for the cumulate olivine is conspicuously higher than the compositional array of the mantle olivine proposed by TAKAHASHI (1986). The maximum content of NiO in the cumulate olivine is 0.22 wt% for dunite, 0.15 wt% for wehrlite, 0.14 wt% for olivine clinoyproxenite, and 0.10 wt% for kaersutite clinopyroxenite. The NiO contents are conspicuously lower than those of the mantle olivine and the compositional range is separated from the NiO mantle olivine array.

Compositional zoning in the olivine grains is rather unclear, due to an adcumulus growth during crystallization of the Turtle Rock cumulates. In particular, no $mg\#$-zoning has been observed in the cumulus olivine, except for an iron-enrichment at the margin in contact with the host basanite. A slight enrichment in MnO and a slight depletion in NiO, however, are detectable at the periphery of the cumulus grains.
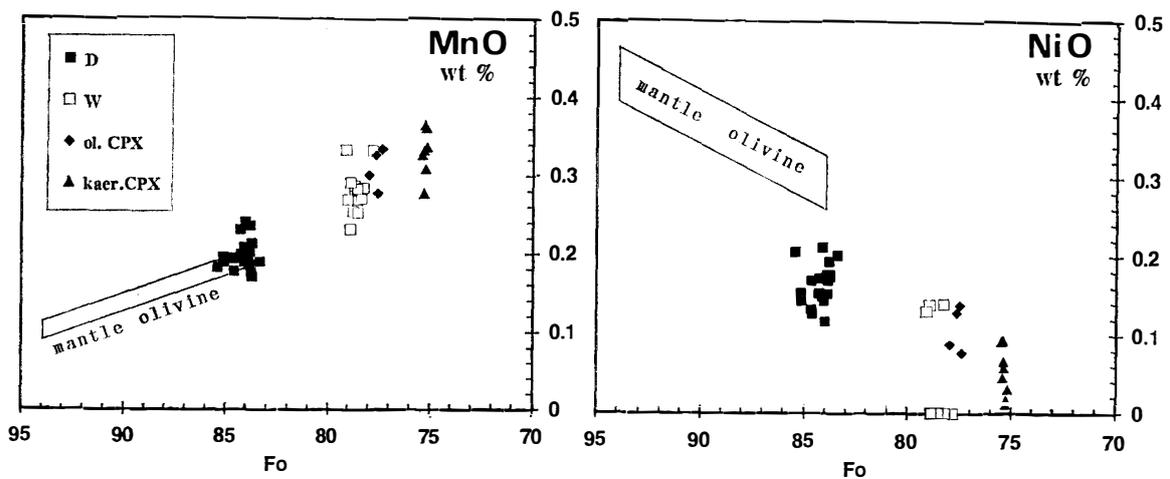
Fig. 4. Plots of MnO and NiO contents against Fo mol % for olivines from the Turtle Rock cumulates. Open boxes labeled with mantle olivine show the compositional range of olivines in mantle-derived spinel lherzolite xenoliths (TAKAHASHI, 1986). D: dunite, W: wehrlite, ol. CPX: olivine clinopyroxenite, kaer. CPX: kaersutite clinopyroxenite.

3.2. Clinopyroxene

The mg♯-number of clinopyroxene from the Turtle Rock cumulates ranges between 85.4–86.9 for dunite, 73.3–81.4 for wehrlite, 71.0–78.6 for clinopyroxenite, and 68.1–72.2 for gabbro.

Figure 5 shows the compositional variations of TiO_2, Al_2O_3, Na_2O, and Cr_2O_3 contents in clinopyroxenes for each rock type of dunite-wehrlite-clinopyroxenite-gabbro cumulates. The TiO_2 content ranges from 0.45 wt% for dunite to 3.24 wt% for clinopyroxenite. The Al_2O_3 content ranges from 3.78 wt% for dunite to 10.93 wt% for clinopyroxenite. The Na_2O content increases from 0.32 wt% for dunite to 1.34 wt% for gabbro with decreasing mg♯-number. The maximum content of Cr_2O_3 decreases from 0.59 wt% for dunite to 0.07 wt% for gabbro with decreasing mg♯-number. As shown in Fig. 5, the compositional range of TiO_2, Al_2O_3, Na_2O, and Cr_2O_3 contents in clinopyroxene from the Turtle Rock cumulates are clearly different from those of the upper mantle clinopyroxenes. The compositional range of the CaO content (20.06–
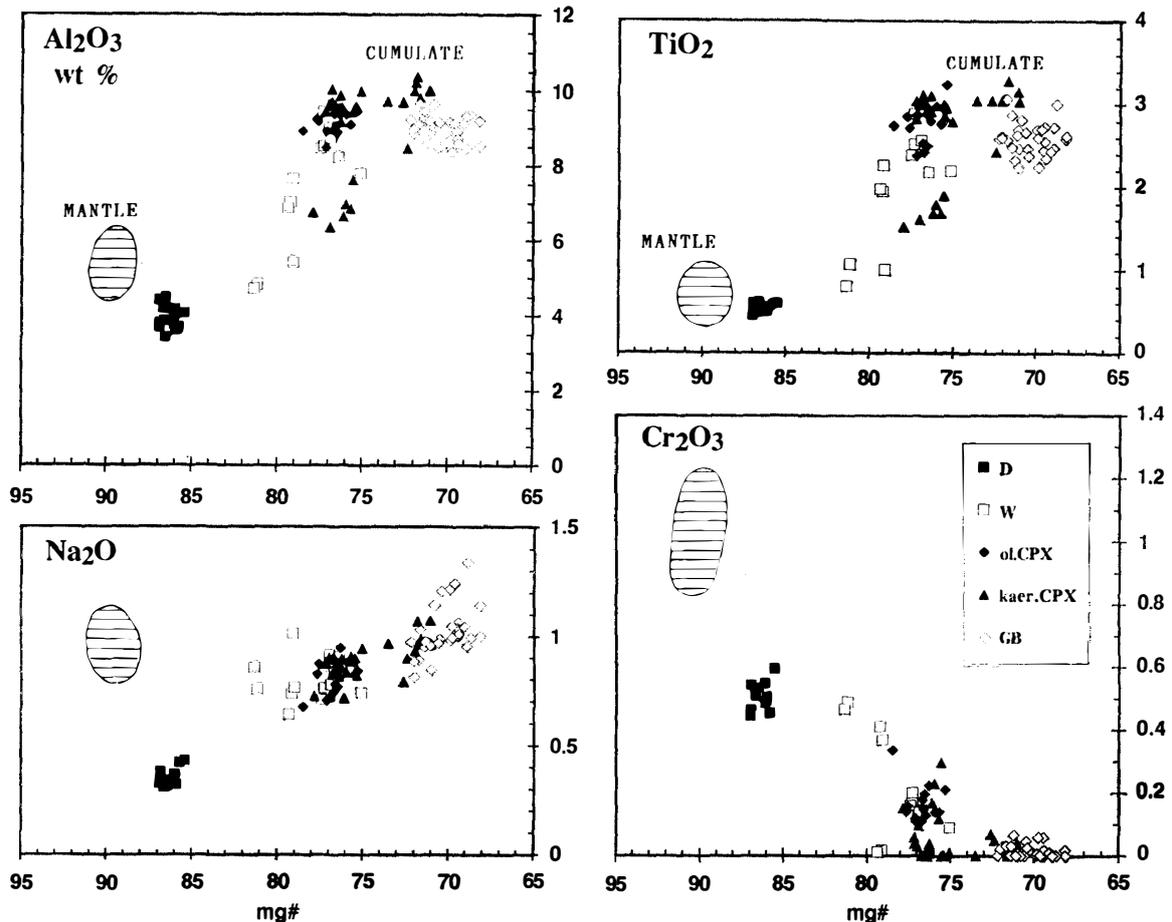
Fig. 5. Plots of Al_2O_3, Na_2O, TiO_2 and Cr_2O_3 contents (wt. %) against mg♯-number (mg♯=100Mg/ (Mg+Fe)) for clinopyroxenes from the Turtle Rock cumulates; D: dunite, W: wehrlite, ol. CPX: olivine clinopyroxenite, kaer. CPX: kaersutite clinopyroxenite, GB: gabbro. Horizontally shaded area labeled as MANTLE represents the compositional range of the upper mantle clinopyroxenes, of which analyses from the Turtle Rock spinel lherzolite (Sample No. 73-5; NIIDA, 1988).

22.52 wt%) against the mg$\sharp$-number overlaps with the Group II clinopyroxenes from Foster Crater (Gamble et al., 1988).

The clinopyroxenes from the Turtle Rock cumulate suite are characteristically rich in TiO_2 and Al_2O_3, and can be classified as titaniferous fassaitic augite in composition. The Ti/Al ratio increases from 0.075 for dunite to 0.22 for clinopyroxenite with a decrease of the mg$\sharp$-number, showing a linear correlation between Ti and Al. Endmember calculations for the Turtle Rock clinopyroxenes indicate that the $Ca(Al, Fe, Cr)AlSiO_6$ and $CaTiAl_2O_6$ molecules increase with decreasing mg$\sharp$-number, ranging between 5.5–21.5 and 1.2–8.5 mol%, respectively. The sodic pyroxene molecules, $Na(Al, Fe, Cr)Si_2O_6$, also increase up to about 13 mol%. Accordingly, the total amount of these three endmembers attains approximately 40 mol% for clinopyroxene in gabbro.

3.3. Kaersutitic amphibole

Titaniferous kaersutitic amphiboles (Ti-pargasites and kaersutites) are abundant in clinopyroxenite and gabbro from the Turtle Rock cumulate suite. Small amounts of kaersutitic amphibole are also observed interstitially in some wehrlites (Sample Nos. 73-7 and 73-16a). The mg$\sharp$-number ranges between 68.8–74.2 for plagioclase-bearing wehrlite, 66.9–71.6 for clinopyroxenite, and 60.1–65.2 for gabbro.

Figure 6 shows the compositional variation of K_2O and TiO_2 contents vs. mg$\sharp$-number in kaersutitic amphiboles from the Turtle Rock cumulates. The K_2O content ranges from 0.92 to 1.40, whereas the TiO_2 content from 4.02 to 6.50. There is no compositional gap between Ti-pargasite and kaersutite. The compositional range of the Turtle Rock cumulates is consistent with those of the cumulates derived from the world-wide subcontinental lithosphere (e.g.; Prinz and Nehru, 1969; Best, 1970; Francis, 1976; Griffin et al., 1984; Gamble and Kyle, 1987). Additionally, it is apparent from Fig. 6 that the K_2O and TiO_2 contents are considerably higher than those of pargasitic amphiboles from the upper mantle peridotites. The Cr_2O_3 content is always less than 0.25 wt%.

3.4. Plagioclase

Plagioclase feldspar is common in gabbro cumulates from Turtle Rock. Trace amounts of plagioclase occur as interstitial crystals in wehrlite (Sample No. 73-16a). The An mol%, ranging between 51.2–58.3 for gabbro and 58.5–80.24 for plagioclase-bearing wehrlite, is typical of igneous cumulates (Fig. 7). The orthoclase content of plagioclase in plagioclase-bearing wehrlite increases steadily with decreasing An %.

3.5. Ti-Fe oxides

Titanomagnetites in kaersutite clinopyroxenite (Sample No. 73-14) and gabbro (Nos. 73-11, 73-15 and 73-24) cumulates were analyzed (Table 1). Ilmenites were found in some gabbro cumulates. The mg$\sharp$-number (mg$\sharp$ = 100 Mg/(Mg + Fe)) of titanomagnetite is less than 20 for all cumulate samples. The cr$\sharp$-number (cr$\sharp$ = 100 Cr/(Cr + Al) is very low, less than 12. High $Fe^{3+}/(Al + Cr + Fe^{3+})$ ratios, ranging from 0.65 to 0.75, are rather characteristic of Ti-Fe oxides in cumulates.

Approximately 21.4–38.7 mol% Fe_2TiO_4 3.5–8.8 mol% Mg_2TiO_4, and 31.0–44.8 mol% $FeFe_2O_4$ are attained from the endmember calculation for the Turtle Rock titano-
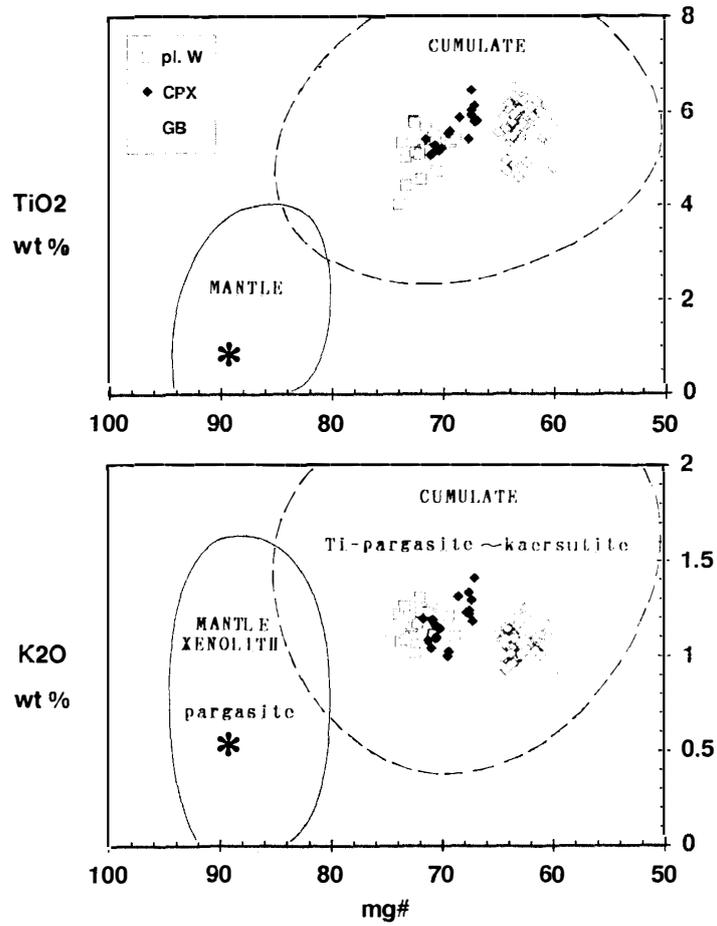
Fig. 6. Compositional variation in K_2O and TiO_2 contents vs. mg#-number for kaersutites from the Turtle Rock cumulates; pl. W: plagioclase-bearing wehrlite, CPX: clinopyroxenite, GB: gabbro, Circled areas with labels CUMULATE and MANTLE show the compositional ranges of kaersutitic amphibole (Ti-pargasite to kaersutite from cumulate inclusions and pargasite from the mantle-derived peridotite xenoliths, respectively (NIIDA et al., in preparation). Mean composition (star*) of insterstitial pargasites from mantle-derived xenoliths (WILKINSON and LE MAITRE, 1987) is shown as a representative for upper mantle amphiboles.
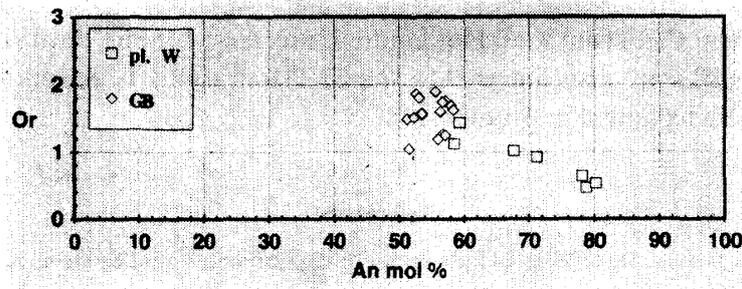
Fig. 7. Plots of Or vs. An mol % for plagioclases from the Turtle Rock cumulates; pl. W: plagioclase-bearing wehrlite, GB: gabbro.

magnetites. The ulvospinel-magnetite solid solutions incorporate up to 4.1 mol% $MgAl_2O_4$ and 9.3 mol% $MgFe_2O_4$.

4. Discussion

Cumulate inclusions, which are commonly entrained by alkaline and highly alkaline magma from the subcontinental lithosphere, have been classified as belonging to the Al-pyroxene-rich suite (Irving, 1974), Al-augite groups (Wilshire and Shervais, 1975), and Group II xenoliths (Frey and Prinz, 1978). The mineralogy of the cumulates is characterized by Fe-rich olivine (abundant), Fe-, Ti- and Al-rich clinopyroxene (titaniferous fassaitic augite; most abundant), and Fe- and Ti-rich Ca-amphibole (titaniferous pargasite to kaersutite). Most of the ferromagnesian silicate minerals have mg#-numbers less than 85 (Frey and Prinz, 1978). Experimental and geochemical evidence suggests that the cumulus assemblages crystallized in the upper mantle (Lloyd and Bailey, 1975, Edgar et al., 1976, Lloyd, 1981; Arima and Edgar, 1983; Duda and Schmincke, 1985). On the other hand, modal and chemical modification of some Group II xenoliths by metasomatism in the upper mantle has been discussed (Lloyd, 1987; Gamble et al., 1988). For example, the Group II(i)-subtype and II(iiib)-subtype clinopyroxenites from West Eifel and Southwest Uganda display notable metasomatic features (Lloyd, 1987). Gamble et al. (1988) also reported the High Calcium Pyroxenite Suite (HCPS) xenoliths from Foster Crater in the foothills of the Trans-antarctic Mountains which contain an unusual Ca-, Mg-rich and Ti-, Cr-poor clinopyroxene.

The Turtle Rock cumulate suite xenoliths described in this paper are considered to be almost identical to the Al-pyroxene-rich suite (Irving, 1974), Al-augite group (Wilshire and Shervais, 1975), and Group II xenoliths (Frey and Prinz, 1978). They show undeformed and unmetasomatized igneous cumulate textures and have wide variations in modal and chemical compositions, as mentioned above. In particular, the compositional range of the Turtle Rock olivines, clinopyroxenes and kaersutitic amphiboles can be specified as "cumulates", which are clearly diffrent from those of mantle-derived lherzolite and pyroxenite xenoliths and also different from those of the Group II(i)-subtype and II(iiib)-subtype clinopyroxenites or the HCPS-type metasomatized xenoliths.

Acknowledgments

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