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Inclusions of phlogopite and phlogopite hydrates in chromite from the Hongguleleng ophiolite in Xinjiang, northwest China

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ABSTRACT

Two types of chromite deposits occur in the Hongguleleng ophiolite in Xinjiang, northwest China. One is located in the mantle sequence, the other occurs in the transition zone between the mantle sequence and layered cumulates. Abundant primary silicate inclusions such as phlogopite, pargasite, clinopyroxene, orthopyroxene, and olivine are found in the segregated chromite, but silicate inclusions occur only rarely in accessory chromite of the ultramafic rocks from the transition zone and cumulates. These silicate phases are considered to have been entrapped as discrete and rare composite inclusions during magmatic precipitation of chromite rather than formed by postmagmatic entrapment.

Phlogopite is the most abundant mineral found as inclusions in chromite in the Hongguleleng ophiolite. There are two types of substitutions for K in the phlogopite inclusions: (1) Na substitutes for K, and phlogopite shows a continuous range from almost pure sodium phlogopite to phlogopite; (2) Ca partially substitutes for K, resulting in the formation of Ca-bearing phlogopite. It is proposed that the alkalic aqueous liquid (melt) responsible for the formation of the phlogopite inclusions was derived from the mixture of the K-rich aqueous liquid related to the subduction of the oceanic slab and the Na-rich aqueous liquid from the primary magma of the ophiolite.

Two types of phlogopite hydrates, hydrate I and possibly a new hydrate (hydrate H), occur as inclusions in the chromite and result from later hydrothermal processes. The fractures from brittle deformation provided passage for meteoric water to enter and react with the phlogopite inclusions.

Compared with those in the transition zone, the inclusions of phlogopite and phlogopite hydrates in the mantle sequence are characterized by (1) smaller grain size and greater abundance, (2) undulatory extinction, (3) higher Si, Cr, Ni, and Ca, and (4) lower Ti and Al. These differences are possibly due to (1) *P, T,* and composition of chromite-precipitating magma, (2) subsolidus reequilibration with the host chromite, and (3) postmagmatic deformation and hydrothermal processes.

INTRODUCTION

Mineral inclusions are found in chromite from ophiolites (Talkington et al., 1984, 1986; Auge, 1987; Auge and Johan, 1988) and layered intrusions (McDonald, 1965; Irvine, 1975; Talkington et al., 1986). The inclusion assemblage in chromite is mainly composed of phlogopite, pargasite, olivine, orthopyroxene, and clinopyroxene. Pt-group minerals (PGM), iron nickel copper sulfides, iron titanium oxides, plagioclase feldspar, apatite, jadeite, purely sodic nepheline, and secondary hydrothermal products (such as serpentine minerals, chlorite, and cummingtonite) have also been reported to occur as inclusions in chromite (Johan et al., 1983; Talkington et al., 1984, 1986; Johan, 1986; Lorand and Cottin, 1987; Lorand and Ceuleneer, 1989; Peng, 1995).

Abundant primary inclusions of phlogopite, pargasite, clinopyroxene, orthopyroxene, and olivine (in decreasing order of abundance) are present in segregated chromite in the Hongguleleng ophiolite. They are only rarely found in accessory chromite of the ultramafic rocks from the transition zone and cumulates. Phlogopite inclusions in the Hongguleleng ophiolite were first reported by Ren and Bai (1986). On the basis of their study, Ren and Bai (1986) reached three conclusions: (1) Besides minor exchange between Mg and Fe, apparent Tschermak's substitution occurs in phlogopite; (2) the "chromitiferous melt" is rich in volatiles, K, Na, and Mg; and (3) phlogopite inclusions (and chromite) in the Hongguleleng

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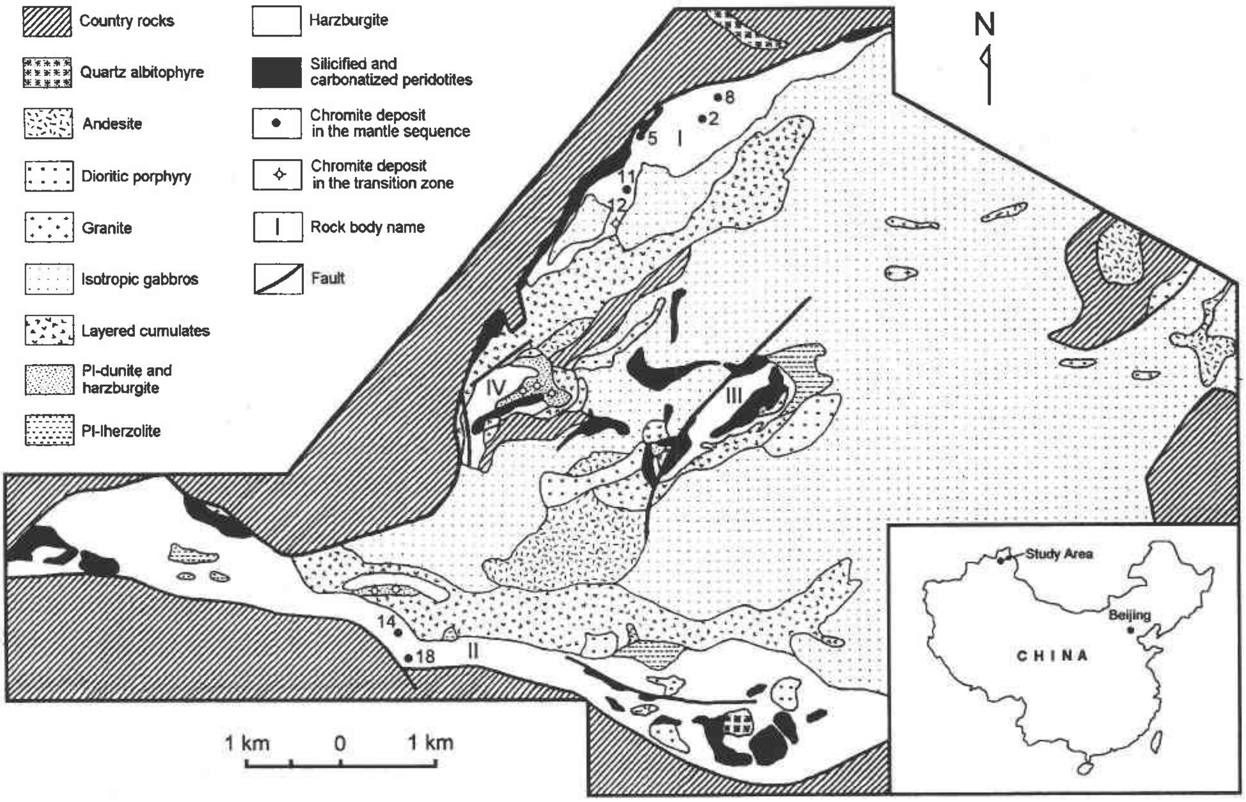

Fig. 1. Geologic map of the Hongguleleng ophiolite.

ophiolite were formed at about 1000 °C and below 10 kbar on the basis of comparison with inclusions in chromite from the Hegenshan ophiolite, Inner Mongolia.

In general, phlogopite in rocks originating from the upper mantle can be classified into four categories according to mode of occurrence: (1) primary phlogopite in peridotites (Aoki, 1974; Delaney et al., 1980; Arai, 1986); (2) secondary phlogopite veining or replacing primary minerals (Delaney et al., 1980; Jones et al., 1982; Arai, 1986); (3) discrete nodules or clots in kimberlites (Aoki, 1974; Dawson and Smith, 1977) and in metasomatic peridotites (Arai and Takahashi, 1989); and (4) inclusions in chromite from ophiolites and layered intrusions (Talkington et al., 1984, 1986; Auge, 1987; Auge and Johan, 1988). Na-rich phlogopite has been found only as inclusions in chromite.

HONGGULELENG OPHIOLITE AND CHROMITE DEPOSITS

Ophiolite

The Hongguleleng ophiolite is located in the northeastern part of the West Junggar Mountains in Xinjiang, northwest China (Fig. 1). The West Junggar region consists of a Paleozoic fold-belt occupying a late Paleozoic zone of convergence of the three major Eurasian plates: Siberian, Tarim, and Kazakhstan (Feng et al., 1989). There are six separate ophiolites, which date from late Cambrian to middle Devonian, in West Junggar. The Hongguleleng ophiolite is the best preserved ophiolite of West Junggar and occupies an area of about 70 km^2. It has a fairly complete ophiolite sequence and is Ordovician in age on the basis of an Sm-Nd reference line of gabbros (Zhang et al., 1993). This ophiolite consists of mantle sequence, transition zone, layered cumulates, isotropic gabbros, basalt, and basaltic andesite. The mantle sequence is composed of harzburgite, lherzolite, plagioclase lherzolite, and dunite. The transition zone consists of harzburgite, dunite, plagioclase dunite, melatroctolite, and olivine gabbro. The layered cumulate sequence is well exposed and contains ultramafic cumulates (dunite and plagioclase dunite) and mafic cumulates (melatroctolite, troctolite, leucotroctolite, olivine gabbro, and gabbro). The isotropic gabbros consist of diabase and gabbros with variable grain sizes. Small segregated plagiogranite pods are found in the mafic cumulates and isotropic gabbros. Rare pillow basalt and abundant massive basaltic andesite adjoin the plutonic sequence and are located in the eastern part of the ophiolite (beyond the region in Fig. 1). In addition, many dikes and veins of diverse composition are scattered throughout both the mantle peridotites and cumulates.

Chromite deposits

There are two types of chromite deposits in the ophiolite. One is located in the mantle sequence, the other occurs in the transition zone. Chromite deposits in the man-

TABLE 1. Selected electron microprobe analyses of the segregated chromite in the Hongguleleng ophiolite

	1	2	3	4	5	6	7	8	9	10
SiO_2	0.00	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.04	0.00
TiO_2	0.15	0.13	0.09	0.27	0.31	0.49	0.37	0.33	0.19	0.23
Al_2O_3	20.63	20.80	19.19	22.72	23.45	22.13	22.51	30.22	33.02	32.45
Cr_2O_3	47.96	48.43	48.02	45.74	44.49	44.95	44.31	36.87	34.24	34.52
Fe_2O_3*	3.48	3.21	3.89	3.31	3.47	4.30	3.92	3.38	3.13	3.17
MgO	15.16	15.83	13.26	15.89	15.98	15.19	14.05	15.16	15.60	15.57
FeO*	12.49	11.39	15.19	11.44	11.31	12.62	14.35	13.82	13.67	13.49
MnO	0.20	0.24	0.28	0.24	0.27	0.25	0.21	0.30	0.19	0.21
NiO	0.14	0.12	0.05	0.16	0.13	0.17	0.17	0.13	0.12	0.12
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
K_2O	0.03	0.02	0.01	—	—	0.02	0.03	0.01	0.02	0.02
Total	100.22	100.20	100.01	99.78	99.40	100.12	99.92	100.23	100.23	99.78
O	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00
Ti	0.03	0.02	0.02	0.05	0.06	0.09	0.07	0.06	0.03	0.04
Al	6.00	6.02	5.71	6.54	6.75	6.42	6.57	8.46	9.11	9.01
Cr	9.37	9.40	9.58	8.84	8.60	8.75	8.68	6.92	6.34	6.43
Fe^{3+}*	0.60	0.55	0.68	0.57	0.59	0.74	0.68	0.56	0.51	0.52
Mg	5.58	5.79	4.99	5.79	5.82	5.57	5.19	5.37	5.44	5.47
Fe^{2+}*	2.63	2.39	3.27	2.39	2.36	2.66	3.03	2.80	2.72	2.71
Mn	0.04	0.05	0.06	0.05	0.06	0.05	0.04	0.06	0.04	0.04
Ni	0.03	0.02	0.01	0.03	0.03	0.03	0.03	0.03	0.02	0.02
$Mg/(Mg + Fe^{2+})$	0.68	0.71	0.60	0.71	0.71	0.68	0.63	0.66	0.67	0.67
$Cr/(Cr + Al)$	0.61	0.61	0.63	0.57	0.56	0.58	0.57	0.45	0.41	0.42

Note: Numbers 1–5, segregated chromite in the mantle sequence; numbers 6–10, segregated chromite in the transition zone.
* Calculated from total Fe by assuming spinel stoichiometry.

tle sequence are found primarily in rock bodies I and II (Fig. 1). They have lenslike or podiform shapes (up to 15 m long) and can be classified as concordant or subconcordant (Cassard et al., 1981). The chromite deposits are surrounded by 0.2–2 m thick dunite envelopes. The segregated chromite is mainly massive, coarse to medium grained, and anhedral to subhedral. A pull-apart texture is common in segregated chromite from the mantle sequence. Original interstitial minerals (olivine and clinopyroxene) of the segregated chromite are mostly altered into serpentine minerals, chlorite, and veined carbonates.

Chromite deposits in the transition zone are mainly located in rock bodies II and IV (Fig. 1) and have nested, veinlike, plumose, or other irregular shapes. The segregated chromite grades into the surrounding plagioclase-bearing rocks. The chromite deposits, along with their surrounding rocks, penetrate harzburgite and crosscut the foliation of the harzburgite, forming dikelike bodies. Therefore, according to the classification of Cassard et al. (1981), the chromite deposits in the transition zone are of the discordant type. Although more than 100 ore clots have been found in the transition zone, they are of little economic interest because of their small size (mostly <8 m^3) and the disseminated nature of the segregated chromite. The segregated chromite is medium to fine grained and subhedral to euhedral. Interstitial minerals in the segregated chromite include olivine, clinopyroxene, orthopyroxene, and plagioclase and have also been altered into secondary minerals (serpentine minerals, amphibole, chlorite, hydrogrossular, and carbonates). Segregated chromite grains in the transition zone commonly occur as discontinuous chains that surround olivine oikocrysts and form a netted structure, similar to those in layered intrusions (Jackson, 1961).

Representative electron microprobe analyses of segregated chromite in the Hongguleleng ophiolite are listed in Table 1. No systematic compositional difference has been detected between chromite grains with and without phlogopite inclusions. Average Cr_2O_3 and Al_2O_3 contents of segregated chromite in the mantle sequence are 47.3 and 21.1 wt%, respectively, but average Cr_2O_3 and Al_2O_3 contents of segregated chromite in the transition zone are 40.5 and 26.5 wt%, respectively. Because of the low concentration of Fe^{3+}, Cr and Al in both types of segregated chromite show an excellent reciprocal relationship (Fig. 2a), which is typical of podiform chromite (Thayer, 1964). Segregated chromite in the mantle sequence generally has higher Cr/(Cr + Al) ratios and a wider range of Mg/(Mg + Fe^{2+}) than that in the transition zone (Fig. 2b). Segregated chromite from the transition zone plots in two separate groups. The relatively Cr-rich and Cr-poor groups are associated with olivine + plagioclase + orthopyroxene and olivine + plagioclase + clinopyroxene assemblages, respectively, which is probably because of the compositional differences in the magma chambers where the chromite crystallized (Lippard et al., 1986; Peng, 1995). Compared with that in the transition zone, segregated chromite in the mantle sequence has lower Ti but similar Ni (Fig. 2c and 2d).

MINERALOGY AND CHEMISTRY OF THE INCLUSIONS OF PHLOGOPITE AND PHLOGOPITE HYDRATES

Occurrence and mineralogy

Phlogopite and phlogopite hydrates have been found only as inclusions in accessory chromite of plagioclase dunite from the transition zone and in segregated chro-

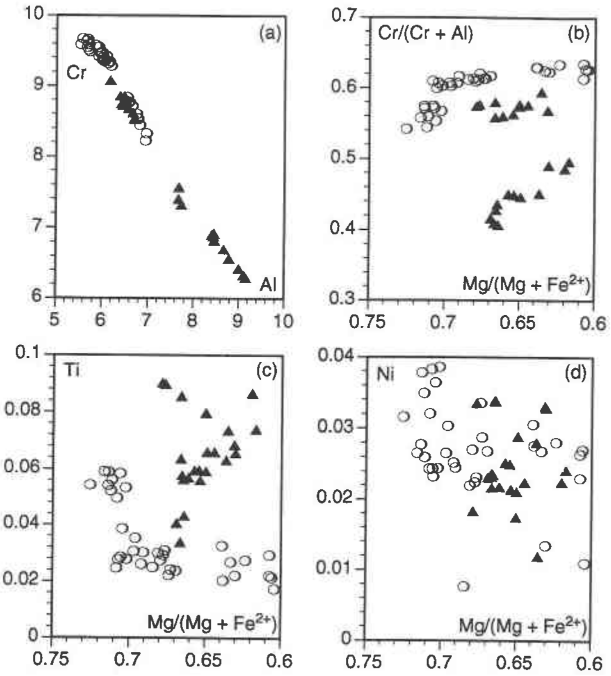

Fig. 2. Compositional variations of the segregated chromite in the Hongguleleng ophiolite (based on 32 O atoms). (**a**) Al vs. Cr, (**b**) Mg/(Mg + Fe^{2+}) vs. Cr/(Cr + Al), (**c**) Mg/(Mg + Fe^{2+}) vs. Ti, and (**d**) Mg/(Mg + Fe^{2+}) vs. Ni. Open circles = segregated chromite in the mantle sequence, solid triangles = segregated chromite in the transition zone.

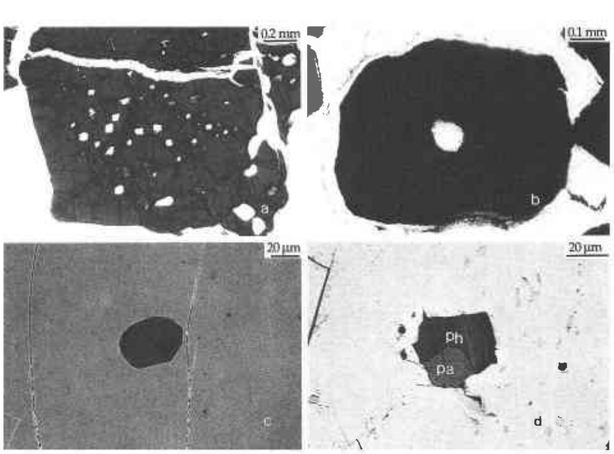

Fig. 3. Silicate inclusions in the segregated chromite. (**a**) Phlogopite inclusions in chromite from the mantle sequence, (**b**) phlogopite inclusion in chromite from the transition zone, (**c**) olivine inclusion in chromite from the mantle sequence, (**d**) phlogopite (ph) and pargasite (pa) composite inclusion in chromite from the transition zone. (**a** and **b**) Plane-polarized transmitted light, (**c** and **d**) backscattered electron images.

mite in the ophiolite. Although some phlogopite and other silicate inclusions have rounded or irregular edges, possibly because of dissolution processes (Leblanc, 1980), most of the silicate inclusions in the Hongguleleng chromite are euhedral or subhedral (Fig. 3a–3d). Phlogopite inclusions in the chromite are predominantly monomineralic, but phlogopite locally coexists with pargasite (Fig. 3d).

A single segregated chromite grain in the mantle sequence can contain more than 15 phlogopite inclusions (Fig. 3a). They are randomly and unevenly distributed. Some chromite grains are rich in inclusions, whereas their neighboring grains may be free of inclusions. The size of the phlogopite inclusions ranges from 3 to 80 µm. Undulatory extinction and a twisted appearance of the phlogopite inclusions are common, suggesting that they experienced structural deformation after they were entrapped.

Compared with those in the mantle sequence, phlogopite inclusions in segregated chromite from the transition zone are larger (20–200 µm) but much fewer in number. An individual chromite grain commonly contains only one phlogopite inclusion, which typically occurs in the central part of the chromite grain (Fig. 3b). These textural features are similar to those in the Bushveld Complex (McDonald, 1965) and opposite to those in the Oman ophiolite (Lorand and Ceuleneer, 1989). Unlike those in the mantle sequence, phlogopite inclusions in the transition zone are locally twinned and show only very weak undulatory extinction. Segregated chromite and the surrounding rocks in the transition zone also indicate that no strong deformation has taken place since their precipitation (Peng, 1995).

The morphology of phlogopite hydrates is similar to that of phlogopite; the phlogopite hydrates are considered to have resulted from later hydration processes (Carman, 1974). Unlike the phlogopite inclusions, which are typically isolated in chromite grains, the phlogopite hydrates are commonly accompanied by radial fractures in chromite, which are possibly caused by the volumetric increase of phlogopite during hydration.

Analytical technique

All analyses were performed using an automated JEOL JXA8900 superprobe with five wavelength-dispersive spectrometers at the U.S. Geological Survey, Reston, Virginia. Analytical conditions were as follows: 15 kV accelerating voltage, 20 nA probe current, 2–5 µm beam diameter, and 20 s counting time for each element. ZAF corrections were used. Standards used for phlogopite and phlogopite hydrates were as follows: labradorite for Na, Ca, Al, and Si; orthoclase for K; titanite for Ti; synthetic tephroite for Mn; chromite for Cr; biotite for Fe and Cl; olivine for Mg; synthetic nickel olivine for Ni; synthetic barium glass for Ba; and synthetic fluorphlogopite for F. Calibrations were checked by analyzing hornblende from Kakanui, New Zealand, and biotite from Lemhi, Idaho, as working standards.

Chemistry

According to the classification of Deer et al. (1962), the micas occurring as inclusions in the Hongguleleng chromite are all phlogopite. A total of 253 phlogopite analyses were performed. In general, concentrations of F and Cl in the phlogopite are very low (0.00–0.25 wt%). Selected analyses are listed in Table 2 and can be divided into three groups. The first group accounts for 60% of the analyses and matches the ideal value of sodium phlogopite, $NaMg_3AlSi_3O_{10}(OH)_2$, with an H_2O content of 4.49 wt% and a total of 95.5 wt%. The remainder of the analyses have lower totals. Replicate analyses and the considerable number of low-summing phlogopite analyses indicate that the low-summing totals are not due to analytical errors. On the basis of an examination of phlogopite by TEM, Yau et al. (1984) found interlayering of phlogopite and chlorite. The average MgO content of chlorite inclusions in chromite from the Hongguleleng ophiolite is 33.4 wt%, higher than the average MgO content of the phlogopite inclusions (25.0 wt%). If the phlogopite is interlayered with the chlorite, the mixture should have a lower total but higher MgO content than the phlogopite. In fact, MgO contents generally decrease from phlogopite to low-summing phlogopite, thus excluding the possibility that the phlogopite is interlayered with its alteration product (chlorite). Low-summing phlogopite shows a general reduction in the weight percentage of most oxides and is here considered to be phlogopite hydrate. Sodium phlogopite hydrates as defined by Carman (1974), that is, hydrate I [$NaMg_3AlSi_3O_{10}(OH)_2 \cdot 2H_2O$] and hydrate II [$NaMg_3AlSi_3O_{10}(OH)_2 \cdot 5H_2O$], have theoretical H_2O contents of 12.4 and 22.0 wt%, respectively. The second group of the analyses in Table 2 approaches the ideal value of hydrate I with a total of 87.6 wt%. The third group has a total near the theoretical total (91.4 wt%) of the formula $NaMg_3AlSi_3O_{10}(OH)_2 \cdot H_2O$, possibly another type of sodium phlogopite hydrate (here we call it "hydrate H" for the convenience of discussion). Hydrate H has not been defined before, but sodium phlogopite in a metamorphic evaporite sequence from Algeria documented by Schreyer et al. (1980) has an average total of 92.0 wt% and most likely belongs to this group. Schreyer et al. (1980) considered that this phlogopite was hydrate I, but this was owing to a miscalculation of the content of H_2O in hydrate I. In the figures in this paper, all hydrates were recalculated into phlogopite for the purpose of comparison.

From Table 2 it is evident that all analyses of phlogopite and phlogopite hydrates show low values in the A site, reflecting alkali depletion. This seems to be a general case for analyses of phlogopite inclusions (Ren and Bai, 1986; Lorand and Cottin, 1987; McElduff and Stumpfl, 1991). In the inclusions no Rb was detected and BaO contents were very low. Average BaO contents of inclusions of phlogopite and phlogopite hydrates in the mantle sequence and in the transition zone are 0.03 and 0.04 wt%, respectively. There are two types of substitutions for K in the inclusions of phlogopite and phlogopite hydrates: (1) Na substitutes for K, forming a continuous range from almost pure sodium phlogopite (K/Na = 0.04) to phlogopite (K/Na = 0.98) (Figs. 4 and 5a); (2) Ca partially substitutes for K, resulting in the formation of Ca-bearing phlogopite (Fig. 4). Both K-rich and Na-rich phlogopite can even be found in the same chromite grain but never coexist in a single inclusion. In pargasite + phlogopite composite inclusions the phlogopite is Na-rich. Average K/(K + Na) values of the phlogopite inclusions in the mantle sequence and transition zone are 0.68 and 0.70, respectively, but average K/(K + Na) ratios of the phlogopite hydrate inclusions in the mantle sequence and transition zone are 0.78 and 0.80, respectively, reflecting the preferential leaching of Na relative to K during the hydration of phlogopite. In addition, inclusions of phlogopite and phlogopite hydrates in the mantle sequence have relatively higher Ca contents than those in the transition zone (Fig. 4).

Average $Mg/(Mg + Fe_t)$ ratios (Fe_t, total Fe as Fe^{2+}) of phlogopite inclusions in the mantle sequence and transition zone are both 0.96, similar to those of the other silicate inclusions such as olivine, orthopyroxene, clinopyroxene, and pargasite (Peng, 1995). The high $Mg/(Mg + Fe_t)$ values of the phlogopite and other silicate inclusions probably result from subsolidus reequilibration between them and the host chromite (Irvine, 1967; Lehmann, 1983; Lorand and Cottin, 1987). Average $Mg/(Mg + Fe_t)$ ratios of phlogopite hydrate inclusions in the mantle sequence and in the transition zone are both 0.94, slightly lower than those of the phlogopite inclusions.

Ti in phlogopite may vary according to the following types of substitutions:

$$2Mg = Ti + \square \quad (\square\text{, vacant site})$$

$$\text{(Forbes and Flower, 1974)} \qquad (1)$$

$$Mg + 2Si = Ti + 2Al \text{ (Robert, 1976).} \qquad (2)$$

High-pressure experiments on rocks in which Ti-rich phlogopite crystallized as a supersolidus mineral supported both of the above proposed substitutions (Edgar et al., 1976; Barton and Hamilton, 1979).

Phlogopite inclusions in the transition zone have higher TiO_2 contents (average TiO_2, 1.91 wt%) than those in the mantle sequence (average TiO_2, 1.21 wt%) (Fig. 5b). Ti contents in the phlogopite hydrates are almost the same as those in the phlogopite (Fig. 5b), which implies that hydration had little effect on the Ti concentration.

Average Cr_2O_3 contents of phlogopite inclusions in the mantle sequence and transition zone are 2.42 and 2.01 wt%, respectively. These contents are much higher than those of primary (average 0.82 wt%) and secondary (average 1.08 wt%) phlogopite from garnet peridotite nodules in the South Africa kimberlites and those of primary (average 1.00 wt%) and secondary (average 1.44 wt%) phlogopite from a spinel (plagioclase) peridotite intrusion in Japan (Delaney et al., 1980; Arai and Takahashi, 1989). Cr and Al in the phlogopite inclusions show a roughly reciprocal correlation (Fig. 5c), which is similar to that in the segregated chromite (Fig. 2a) and inverse to that of primary- and secondary-textured phlogopite in garnet pe-

TABLE 2. Selected electron microprobe analyses of the inclusions of phlogopite and phlogopite hydrates in the Hongguleleng ophiolite

	Phlogopite				Hydrate H			Hydrate I	
	1	2	3	4	5	6	7	8	9
SiO_2	40.62	40.36	39.88	40.06	37.91	40.12	36.92	38.29	36.28
TiO_2	1.08	1.03	1.17	1.00	2.26	0.78	1.13	1.09	0.94
Al_2O_3	17.29	16.40	17.16	16.16	16.12	14.01	15.49	15.94	14.09
Cr_2O_3	2.50	2.48	2.34	2.25	2.11	2.61	2.64	2.15	2.68
MgO	25.40	25.19	24.78	25.07	22.61	22.32	26.13	24.03	22.96
FeO	1.17	1.03	1.08	1.16	2.56	6.01	2.32	0.89	5.24
MnO	0.03	0.04	0.00	0.02	0.03	0.05	0.09	0.05	0.04
NiO	0.55	0.49	0.38	0.46	0.31	0.36	0.63	0.59	0.37
CaO	0.27	0.39	0.05	0.02	0.13	3.44	1.69	0.18	0.21
BaO	0.09	0.00	0.09	0.04	0.00	0.00	0.00	0.09	0.03
Na_2O	6.25	0.53	2.07	0.45	0.57	0.16	0.30	3.44	0.58
K_2O	0.50	8.31	6.33	8.55	7.72	2.87	4.32	1.94	3.52
F	0.04	0.17	0.04	0.00	0.00	0.00	0.00	0.24	0.00
Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−O = F,Cl	−0.02	−0.07	−0.02	0.00	0.00	0.00	0.00	−0.10	0.00
Total	95.76	96.35	95.35	95.25	92.32	92.72	91.65	88.81	86.93
O	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00
Si	5.50	5.57	5.52	5.60	5.49	5.75	5.33	5.59	5.54
Al	2.76	2.67	2.80	2.66	2.75	2.37	2.64	2.74	2.54
Ti	0.11	0.11	0.12	0.10	0.25	0.08	0.12	0.12	0.11
Cr	0.27	0.27	0.26	0.25	0.24	0.30	0.30	0.25	0.32
Mg	5.13	5.19	5.11	5.22	4.88	4.77	5.62	5.23	5.23
Fe	0.13	0.12	0.13	0.14	0.31	0.72	0.28	0.11	0.67
Mn	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00
Ni	0.06	0.05	0.04	0.05	0.04	0.04	0.07	0.07	0.05
Ca	0.04	0.06	0.01	0.00	0.02	0.53	0.26	0.03	0.03
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	1.64	0.14	0.55	0.12	0.16	0.04	0.08	0.97	0.17
K	0.09	1.46	1.12	1.52	1.43	0.53	0.80	0.36	0.69
Sum	15.73	15.64	15.66	15.66	15.57	15.14	15.51	15.48	15.35

Note: Numbers 1–9, inclusions in the mantle sequence; numbers 10–18, inclusions in the transition zone.

ridotite xenoliths from the South Africa kimberlites (Delaney et al., 1980). The phlogopite hydrate inclusions have Al and Cr contents similar to those of the phlogopite inclusions in the corresponding sequences.

Al in phlogopite may vary according to the following four kinds of substitutions:

$$\text{Mg} + \text{Si} = 2\text{Al (Tschermak's substitution)} \tag{3}$$

$$2\text{Si} + \Box = \text{Mg} + 2\text{Al (Seifert and Schreyer, 1971)} \tag{4}$$

$$\text{Mg} + 2\text{Si} = \text{Ti} + 2\text{Al (Robert, 1976)} \tag{5}$$

$$3\text{Mg} = 2\text{Al} + \Box \text{ (Seifert and Schreyer, 1971).} \tag{6}$$

Of these, Tschermak's substitution is the most significant in phlogopite inclusions of the Hongguleleng chromite because their (Mg + Fe_t)/Si ratios are near unity (Fig. 5a). Average (Mg + Fe_t)/Si values of phlogopite inclusions from the mantle sequence and transition zone are 0.94 and 0.96, respectively. Al in the phlogopite inclusions can thus be expressed as the solution of eastonite [$K_2Mg_5Al(Si_5Al_3O_{20})(OH)_4$] component in phlogopite. The fact that the average (Mg + Fe_t)/Si ratio of the phlogopite inclusions is a little lower than unity may be due to small amounts of Ti substituting for Mg (or Fe) shown by Equation 1 (Arai, 1984).

Inclusions of phlogopite hydrates in the Hongguleleng ophiolite have similar Ni contents as phlogopite inclusions from the corresponding occurrences (Fig. 5d). Although the two types of segregated chromite have similar Ni contents (Fig. 2d), phlogopite inclusions in the mantle sequence have higher Ni contents (average NiO, 0.43 wt%) than those in the transition zone (average NiO, 0.25 wt%) (Fig. 5d). Ni partition coefficient between olivine and spinel (X^{Ol}_{Ni}/X^{Sp}_{Ni}) correlates positively with the Cr/(Cr + Al) ratio of the spinel and inversely with the equilibrium temperature (Stosch, 1981; Peng, 1995). Thus, olivine inclusions in Cr-rich segregated chromite are richer in Ni than those in Al-rich segregated chromite in West Junggar as a result of subsolidus reequilibration (Peng, 1995). The similarity of Ni partitioning between phlogopite and spinel and between olivine and spinel suggests that subsolidus reequilibration is probably responsible for the difference in Ni content of the phlogopite included in the different types of chromite.

DISCUSSION

There has been extensive discussion in the literature as to the occurrence and origin of the variety of inclusions reported within chromite from both ophiolites and layered intrusions (Leblanc, 1980; Johan et al., 1982, 1983; Talkington et al., 1984, 1986; Lorand and Cottin, 1987; Lorand and Ceuleneer, 1989; McElduff and Stumpfl, 1991). The controversy is concerned mainly with (1) the modes of inclusion entrapment, (2) the nature of the parental material of the inclusions, and (3) the conditions of formation of the inclusions. The following discussion

TABLE 2.—*Continued*

Phlogopite				Hydrate H			Hydrate I	
10	11	12	13	14	15	16	17	18
39.78	38.68	40.00	39.08	38.81	39.06	36.90	32.42	33.30
1.58	1.72	1.61	3.53	1.54	3.55	1.70	1.70	1.80
18.25	17.00	17.10	17.14	18.07	17.33	16.87	17.50	16.47
2.00	1.49	1.81	1.83	2.14	1.84	1.54	1.98	1.94
25.31	24.69	24.41	22.25	24.61	22.40	24.45	26.85	24.54
1.37	1.88	1.51	2.61	1.23	2.56	2.75	3.46	3.21
0.00	0.06	0.05	0.04	0.00	0.01	0.00	0.74	0.23
0.16	0.24	0.28	0.25	0.21	0.21	0.20	0.26	0.29
0.07	0.10	0.12	0.13	0.44	0.38	0.10	0.96	1.02
0.12	0.01	0.00	0.06	0.00	0.13	0.00	0.00	0.00
3.61	0.68	0.33	0.67	3.99	3.32	0.28	0.08	0.20
4.44	8.48	8.79	8.07	0.35	1.39	8.26	2.24	3.74
0.04	0.17	0.00	0.08	0.00	0.11	0.09	0.00	0.04
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−0.02	−0.07	0.00	−0.03	0.00	−0.05	−0.04	0.00	−0.02
96.70	95.12	96.00	95.70	91.38	92.25	93.10	88.19	86.76
22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00
5.40	5.44	5.54	5.46	5.44	5.49	5.32	4.85	5.08
2.92	2.82	2.79	2.82	2.99	2.87	2.87	3.09	2.96
0.16	0.18	0.17	0.37	0.16	0.38	0.18	0.19	0.21
0.22	0.17	0.20	0.20	0.24	0.20	0.18	0.23	0.23
5.12	5.17	5.04	4.63	5.15	4.69	5.26	5.99	5.58
0.16	0.22	0.17	0.31	0.14	0.30	0.33	0.43	0.41
0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.09	0.03
0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.04
0.01	0.02	0.02	0.02	0.07	0.06	0.02	0.15	0.17
0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
0.95	0.18	0.09	0.18	1.08	0.90	0.08	0.02	0.06
0.77	1.52	1.55	1.44	0.06	0.25	1.52	0.43	0.73
15.74	15.76	15.61	15.46	15.35	15.17	15.78	15.50	15.50

is confined mainly to the origin of the inclusions of phlogopite and phlogopite hydrates in chromite from the Hongguleleng ophiolite.

Time and conditions of the formation of the phlogopite inclusions

The phlogopite and other silicate inclusions are ran-

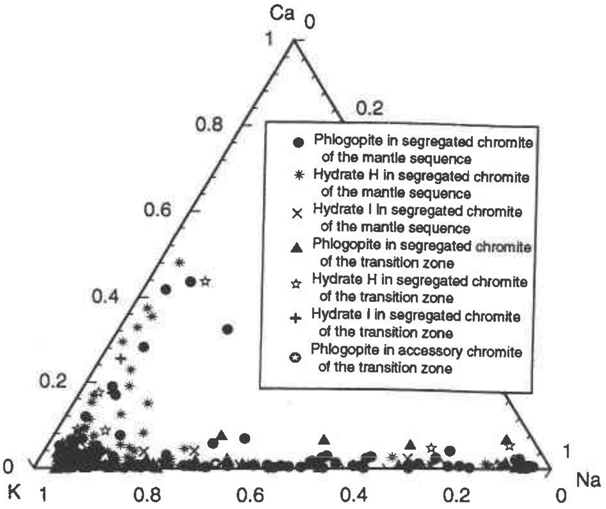

Fig. 4. Plot of K-Na-Ca of the inclusions of phlogopite and phlogopite hydrates in the Hongguleleng ophiolite.

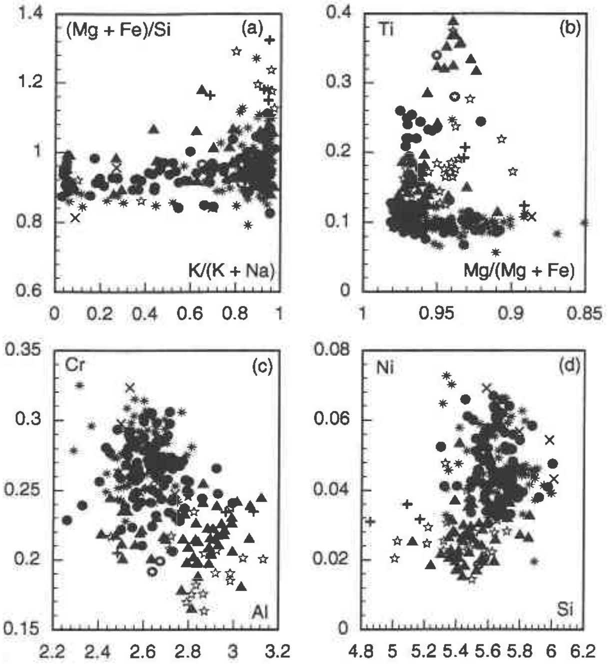

Fig. 5. Compositional variations of the inclusions of phlogopite and phlogopite hydrates in the Hongguleleng ophiolite (based on 22 O atoms). (**a**) K/(K + Na) vs. (Mg + Fe_t)/Si, (**b**) Mg/(Mg + Fe_t) vs. Ti, (**c**) Al vs. Cr, and (**d**) Si vs. Ni. Symbols as in Fig. 4. Fe is total Fe as Fe^{2+}.

domly and unevenly distributed in chromite and are commonly euhedral to subhedral (Fig. 3a–3d), contrary to postmagmatically entrapped inclusions, which tend to be spherical in appearance (Lorand and Cottin, 1987). In addition, textures of segregated chromite in Hongguleleng, such as chromite net and occluded silicate textures, suggest an origin by magmatic accumulation. Lorand and Ceuleneer (1989) hypothesized that both anhydrous silicates (olivine, orthopyroxene, clinopyroxene, or plagioclase) and melt were entrapped during the crystallization of chromite and that these silicates and melt reacted with each other inside the chromite to form phlogopite (pargasite or albite). Because pargasite (phlogopite) inclusions are predominantly monomineralic, and anhydrous silicates coexist only rarely with phlogopite in individual inclusions in Hongguleleng, this hypothesis must assume that chromite proportionally entrapped anhydrous silicates and melt in individual inclusions. It seems that this assumption is not valid for natural systems. Therefore, primary silicate inclusions in the Hongguleleng chromite were probably entrapped as discrete, though locally as composite, inclusions during the magmatic precipitation of chromite.

Eastonite component in the phlogopite from garnet peridotite and spinel peridotite facies rocks is dependent on the equilibrium pressure and temperature (Arai, 1984). Phlogopite derived from deeper regions (garnet peridotite and cores of kimberlite macrocrysts) is generally lower in Al and higher in Si than that derived from shallower regions (spinel peridotite and rims of kimberlite macrocrysts) (Arai, 1984). Phlogopite inclusions in the Hongguleleng mantle sequence have lower Al and higher Si than those in the transition zone (Fig. 5c and 5d), which implies that the former were possibly formed under higher pressures or temperatures than the latter. Phlogopite is rare whereas amphibole is common in spinel or plagioclase peridotite (Francis, 1976; Arai, 1984), but phlogopite is more common than amphibole in the rocks derived from the garnet peridotite region (Dawson, 1980). These observations are consistent with the experimental results indicating that, with increasing pressure, the stability temperature of amphibole shrinks but the stability field of phlogopite expands (Helz, 1982; Montana and Brearley, 1989). In the Hongguleleng ophiolite, the ratio of phlogopite inclusions vs. pargasite inclusions in the mantle sequence (32:1) is much higher than that in the transition zone (2:1), which implies that the former were formed in a deeper environment than the latter.

Carman (1974) pointed out that sodium phlogopite decomposes to forsterite, liquid, and vapor at 5 kbar and 1010 °C. Montana and Brearley (1989) suggested that phlogopite reacts with enstatite to form forsterite and liquid under the conditions of 5 kbar and 1030 °C or 15 kbar and 1140 °C. The mantle peridotites in Hongguleleng have mainly an assemblage of olivine + orthopyroxene + clinopyroxene + spinel, which exists only in a pressure range from 8 to approximately 25 kbar (Kohler and Brey, 1990). Ti tends to stabilize phlogopite with respect to pyroxene because of the reluctance of Ti to enter pyroxene at high pressures (Forbes and Flower, 1974). In the Hongguleleng ophiolite, average TiO_2 contents of phlogopite inclusions in the mantle sequence and transition zone are 1.21 and 1.91 wt%, respectively. Thus, the stability temperature of the phlogopite inclusions should be higher than that of pure phlogopite because of the effect of Ti. In addition, the stability temperature of chromite is normally between 1200 and 1250 °C at $f_{O_2} > 10^{-8.5}$ atm (Hill and Roeder, 1974; Fisk and Bence, 1980). On the basis of the stability temperatures of phlogopite and chromite and the morphology of the phlogopite inclusions, we propose that phlogopite inclusions in the Hongguleleng ophiolite were formed at about 1200 °C.

Formation mechanism of the inclusions of phlogopite and phlogopite hydrates

Phlogopite could be generated by the reaction of alkalic aqueous liquid (melt) with olivine, pyroxenes, or garnet (Yoder and Kushiro, 1969; Delaney et al., 1980; Exley et al., 1982). The abundance of phlogopite inclusions in the Hongguleleng chromite suggests the presence of alkalic aqueous liquid in the mantle sequence and transition zone of the ophiolite during the precipitation of chromite. It has been proposed that the alkalic aqueous liquid responsible for the formation of phlogopite in mantle-related rocks is derived from (1) hydrothermal circulation of seawater (Watkinson and Mainwaring, 1980), (2) subduction of the oceanic lithosphere (Auge, 1987; Lorand and Ceuleneer, 1989); (3) decrease of pressure related to the opening of the ore-forming system (Johan, 1984, 1986), (4) a small degree of partial melting of the mantle (Exley et al., 1982). There are several reports of Na-rich phlogopite and pargasite inclusions in chromite from layered intrusions, which were obviously formed in continental environments without seawater (Talkington et al., 1986; Lorand and Cottin, 1987). In addition, the rocks of ophiolite sequences have extremely low K content (Coleman, 1977). The occurrence of both Na-rich and K-rich phlogopite inclusions in the Hongguleleng chromite implies that the alkalic aqueous liquid generating them could not have evolved from only the primary magma of the ophiolite sequence. The Hongguleleng ophiolite is considered to be formed in a back-arc basin environment chiefly on the basis of its rock association and mineral compositions (Peng, 1995). Here we propose that the alkalic aqueous liquid responsible for the formation of phlogopite inclusions is derived from the mixture of the K-rich aqueous liquid from the subduction of the oceanic slab and the Na-rich aqueous liquid from the primary magma of the ophiolite. Most of the Na probably comes from the melting of clinopyroxene in the upper mantle. The clinopyroxene, an Na-bearing phase and an early mineral to enter the melt, is also the most important source of Cr in the formation of chromite in ophiolites (Dickey, 1975; Mysen and Kushiro, 1977; Johan and Ohnenstetter, 1989). On the basis of a study of O-H-Sr-

Nd isotopes, Dunlop and Fouillac (1986) concluded that podiform chromite from the Oman ophiolite was formed by magmatic crystallization processes. In addition, they considered that alkalic aqueous liquid responsible for the formation of OH-bearing silicate inclusions migrated from the subducted slab and reequilibrated with the overlying mantle wedge (Dunlop and Fouillac, 1986). The broad range in K/Na ratios of phlogopite inclusions in the Hongguleleng chromite probably reflects the wide compositional variation of the alkalic aqueous liquid during the precipitation of chromite.

Phlogopite occurs only as inclusions in the Hongguleleng chromite. This is probably because of the protection provided by the host chromite. The change of chemical and physical conditions following the crystallization of chromite was probably beyond the stability field of phlogopite, resulting in the decomposition of the phlogopite that might have occurred in peridotites and matrix of segregated chromite. Among all phlogopite occurrences in rocks originating from the upper mantle, Na-rich phlogopite has been found only as inclusions in chromite. This suggests that Na-rich phlogopite possibly has a very strict stability field and is stable only within chromite.

According to Carman (1974), at 1 kbar, sodium phlogopite and H_2O-rich vapor react to form hydrate I at 345 °C and hydrate II at 87 °C. Because Na was preferentially leached out of phlogopite inclusions relative to K during hydration (Figs. 4 and 5a), and because hydrothermal seawater circulation is unlikely to penetrate deep into the mantle (McElduff and Stumpfl, 1991), phlogopite hydrates probably formed by the reaction of phlogopite with meteoric water after the emplacement of the ophiolite. During the emplacement, the ophiolite experienced brittle deformation, resulting in the formation of minute fractures in the rocks. The fractures provided passage for meteoric water to penetrate the chromite grains and react with the phlogopite.

Implications for the genesis of chromite and ophiolite

The implications of the above discussion for the genesis of chromite and ophiolite are as follows: First, the existence of phlogopite and pargasite in the chromite suggests that there was high-temperature alkalic aqueous liquid in the chromite-precipitating magma chambers. Second, the compositional differences of the inclusions and segregated chromite imply that the chromite-precipitating magma in the mantle sequence is distinct in composition from that in the transition zone. Third, although chromite deposits in the mantle sequence and those in the transition zone are only a few hundred meters apart in the field, the former might have been formed in much deeper magma chambers within the mantle peridotites than the latter. The phlogopite inclusions, segregated chromite, and surrounding rocks in the transition zone all display the features of weak deformation, suggesting that they were formed after the mantle deformation peak had passed. Lastly, phlogopite and phlogopite hydrates have not been found in accessory chromite of harzburgite, lherzolite, and plagioclase lherzolite from the mantle sequence, but accessory chromite of plagioclase dunite from the transition zone contains phlogopite inclusions with compositions similar to those of phlogopite in segregated chromite of the transition zone (Fig. 5a–5d). This supports an origin of magmatic crystallization for plagioclase dunite in the transition zone (Peng, 1995).

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