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Major-element trend for shergottite melts and their source materials

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Abstract: The major-element compositions of shergottite melts, plotted against their mg [Mg/(Mg+Fe)] atomic ratios, form a narrow trend, which is designated "the shergottite melt trend". Although the mg ratios range from 0.7 to 0.2, the silica contents of the trend are nearly constant from 47 to 53 wt%, indicating that the shergottite melts are basaltic, never andesitic nor komatiitic. The trend is enriched in FeO with the range from 15 to 22 wt%, and poor in Al_2O_3 with the range from 4 to 14 wt%.

The melts for nakhlites are poorer in SiO_2 and Al_2O_3 and richer in FeO than the shergottite melt trend. Although the melts for chassignite are similar to the shergottite melt trend, the melts for chassignite and nakhlites are more enriched in K_2O contents than the shergottites melts, indicating that they have a different origin from the latter.

The bulk major-element compositions of terrestrial basalts, lunar basalts, and eucrites are compared to the shergottite melt trend. The terrestrial basalts and komatiites are poorer in FeO and richer in Al_2O_3, CaO, and Na_2O than the shergottite melt trend. The lunar low-Ti mare basalts and eucrites have rather similar compositions to the shergottite trend. However, their alkali and P_2O_5 contents are low in comparison to the shergottite trend, reflecting their planetary compositions.

A plausible source material for olivine-phyric shergottites was estimated, and it may be a plagioclase peridotite with an mg ratio of 0.81 depleted in alkalis, CaO and Al_2O_3 contents. The partial melting to produce the shergottite trend may have taken place at low pressures, whereas the nakhlites and chassignite may have been produced under moderate (1–30 kb) pressure conditions. The chassignite may have fractionated under a low-pressure condition to produce a large amount of cumulus olivine, whereas the nakhlites have not.

key words: shergottite melts, nakhlite melts, chassignite melts, SNC meteorites, fractional crystallization

1. Introduction

Parental melts for martian meteorites are estimated by many authors, as shown below. Among them, both basaltic and olivine-phyric shergottites are basaltic or doleritic in lithology, and their whole rock compositions may almost represent the parental melts except some cumulus or xenocrystic phases in them. The compositions of groundmasses of basaltic and olivine-phyric shergottites represent the parental or fractionated melts. On the other hand, lherzolitic shergottites, nakhlites, and chassignite are cumulative rocks in lithology, and their whole rock compositions are not representative of the parental melts. The parental melts for these cumulative meteorites are mostly taken to be intercumulus melts. Some martian meteorites contain magmatic inclusions, and the compositions of the trapped melts may be parental melts or the early-stage melts of their crystallization.

Recently, some martian meteorites have been recovered from hot deserts (the Sahara deserts etc.) and cold deserts (Antarctica), and the total number of the martian meteorites is now up to 32, as of August 2004. Therefore, the parental and fractionated melts for many martian meteorites have been obtained enough to summarize them. In this paper, the major-element compositions of the parental and fractionated melts for the martian meteorites are summarized, and a source material for olivine-phyric shergottites is estimated.

2. Parental and fractionated melts for shergottites

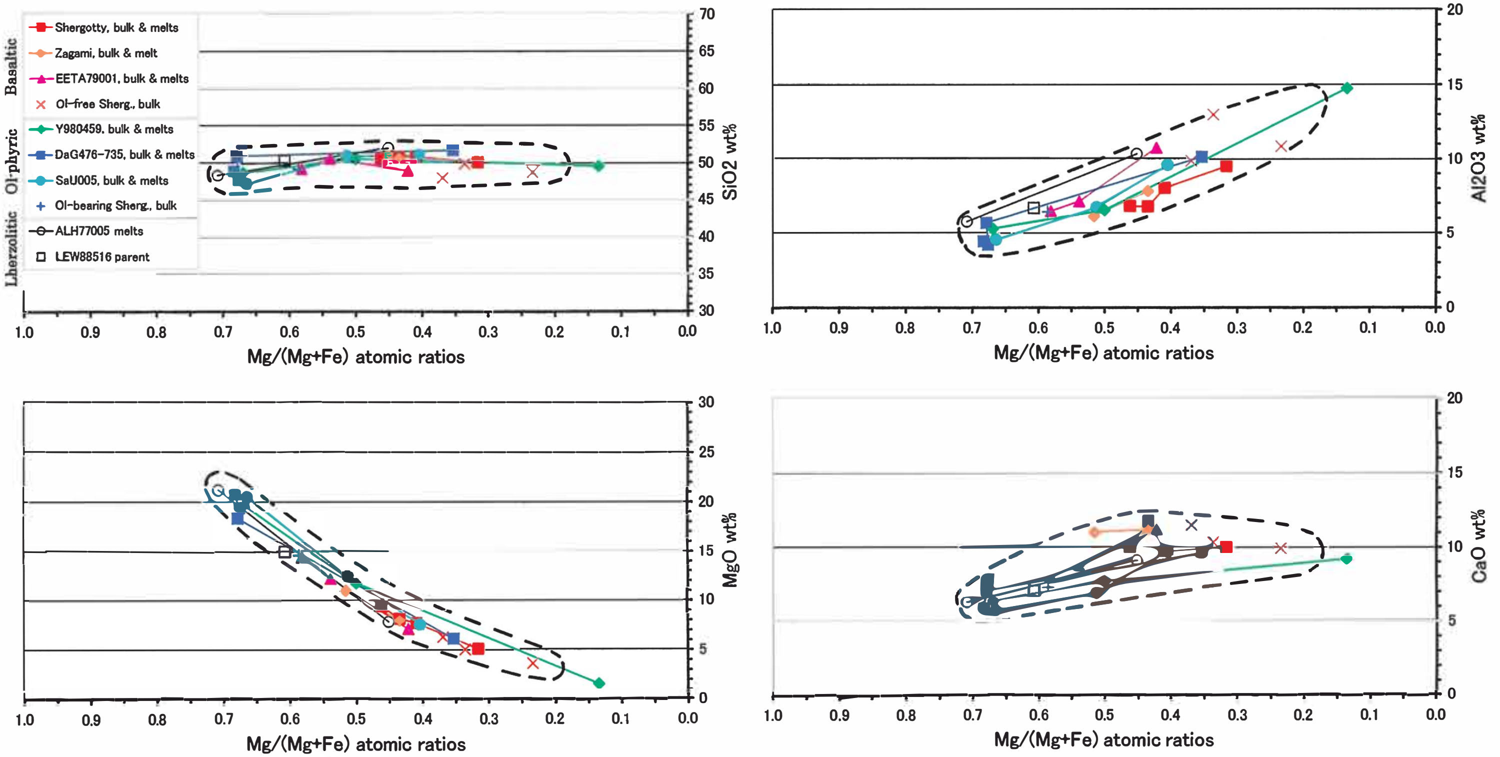
The major-element compositions of the parental and fractionated melts for the shergottites have been estimated by many authors using the following methods. (1) The bulk compositions of some shergottites represent the parental magmas on an assumption that cumulus phases or xenocrysts are absent or minor in them (Wadhwa *et al.*, 1994; McSween *et al.*, 1996; Ikeda, 2004). (2) Many olivine-phyric and basaltic shergottites contain cumulus or xenocrystic phases (Lentz and McSween, 2000), and the parental melts are obtained by the subtraction of them from the whole rock compositions (Wadhwa *et al.*, 2001; Barrat *et al.*, 2002). (3) Lherzolitic shergottites are cumulates, and the parent magmas are taken to be intercumulus melts, which were obtained by subtraction of cumulus phases from the bulk compositions (Lundberg *et al.*, 1990). (4) The groundmass in some shergottites may represent the parental or fractionated melts (McSween and Jarosewich, 1983). (5) Magmatic inclusions occur in some shergottites, and they are used to obtain the initial trapped melts (Ikeda, 1998). (6) Parental melt compositions are calculated by using the partition coefficients between the constituent minerals and the coexisting melts, based on the experimental results (Longhi and Pan, 1989).

3. Shergottite melt trend

The estimated melt compositions for shergottites are plotted in Fig. 1, indicating that all shergottite melts for olivine-phyric, basaltic and lherzolitic shergottites form a narrow major-element trend. This trend is here designated as “The Shergottite Melt Trend”. The data plotted in Fig. 1 are explained in detail as follows.

3.1. Melts for basaltic shergottites

Some basaltic shergottites contain cumulus phases. The Shergotty basaltic shergottite contains cumulus phases, and the intercumulus liquid composition was estimated using partial melting experiments (Stolper and McSween, 1979). Another melt for Shergotty was obtained by subtraction of the cumulus phases from the whole


Shergotty, bulk & melts
Zagami, bulk & melt
EETA79001, bulk & melts
Ol-free Sherg., bulk
Y980459, bulk & melts
DaG476-735, bulk & melts
SaU005, bulk & melts
Ol-bearing Sherg., bulk
ALH77005 melts
LEW88516 parent
Basaltic
Ol-phyric
Lherzolitic
SiO2 wt%
70
65
60
55
50
45
40
35
30
Al2O3 wt%
MgO wt%
CaO wt%
20
15
10
5
0
30
25
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Mg/(Mg+Fe) atomic ratios

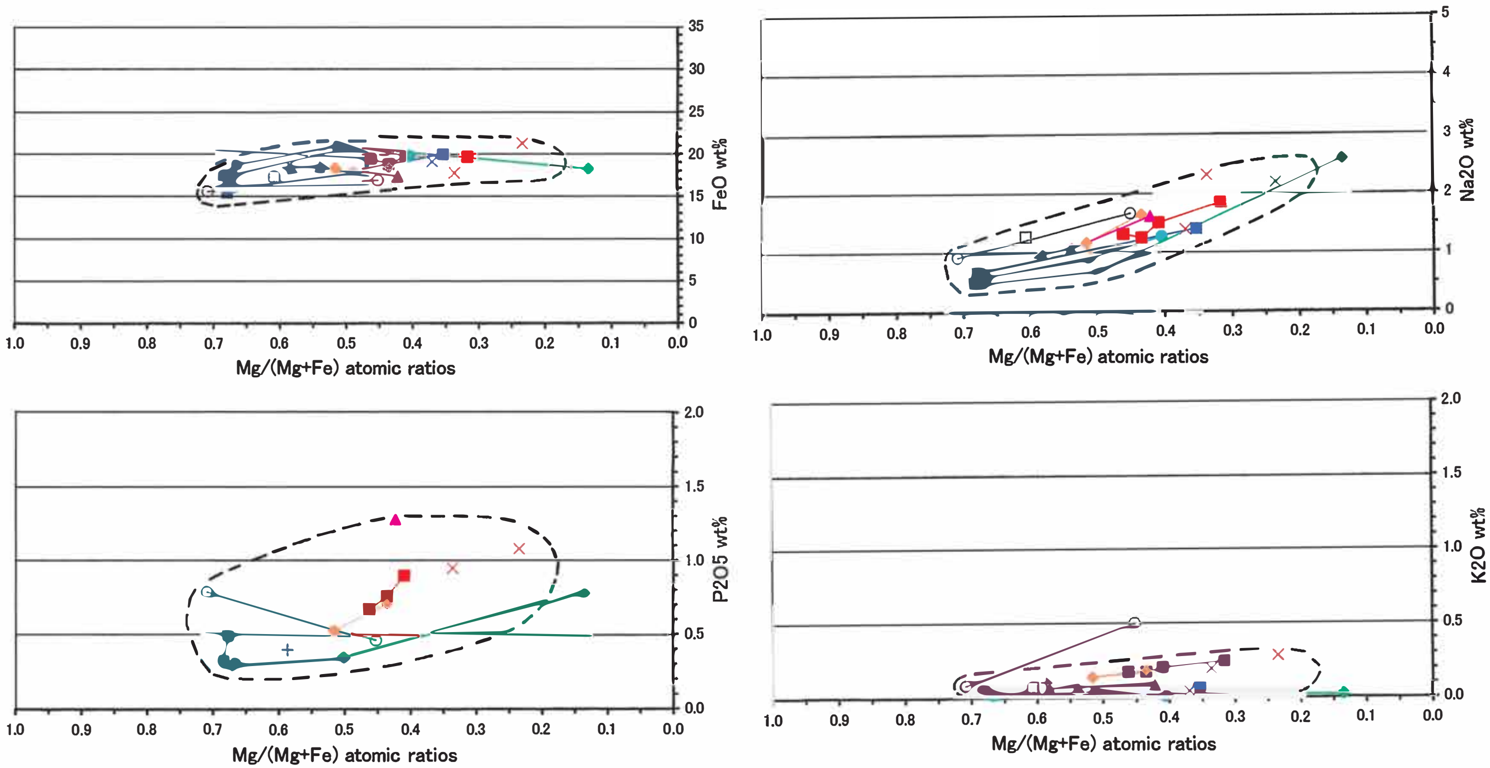


Fig. 1. Shergottite melt trend. FeO is total irons containing FeO and Fe_2O_3. Basaltic, olivine-phyric, and lherzolitic shergottite melts are shown by reddish, bluish, and open symbols, respectively. The groundmass composition of Y980459 was produced by metastable crystallization and is excluded from the shergottite melt trend (see text). Data sources for shergottite melts are: Dann et al. (2001), Dreibus et al. (2000), Folco et al. (2000), Hale et al. (1999), Harvey et al. (1993), Ikeda (1997, 1998, 2004), Lundberg et al. (1990), Longhi and Pan (1989), McCoy et al. (1992), McSween and Jarosewich (1983), Misawa (2003), Rubin et al. (2000), Stolper and McSween (1979), Taylor et al. (2000), Warren et al. (2000), Zipfel et al. (2000).

rocks (Hale *et al*., 1999; SILC for Shergotty Intercumulus Liquid Composition). A third parental melt for Shergotty was also estimated by addition of saturated minerals to the intercumulus liquid (Dann *et al*., 2001, SILC + 15 wt% of augite). The above three melt compositions for Shergotty and the whole rock composition are plotted in Fig. 1. Zagami is very similar to Shergotty, and the chemical composition of the groundmass is taken to be intercumulus liquid (McCoy *et al*., 1992). It is plotted in Fig. 1 together with the whole rock composition of Zagami.

Generally speaking, basaltic shergottites seem to have formed essentially by progressive (closed-system) fractional crystallization (Wadhwa *et al*., 1994), suggesting that their whole rock compositions could represent their melts. The QUE 94201 basaltic shergottite represents a magma unaffected by crystal accumulation (McSween *et al*., 1996). The whole rock compositions of Dhofar 378 and Los Angeles basaltic shergottites, which are very similar to each other, also seem to represent their melts (Warren *et al*., 2004; Ikeda, in preparation). Therefore, the bulk compositions of QUE 94201, Dhofar 378, and Los Angeles are plotted in Fig. 1. The whole rock composition of EETA79001 lithology B may represent the melt, although EETA79001 lithology A contains xenocrysts abundantly (McSween and Jarosewich, 1983). The groundmass composition of the lithology A was calculated by subtraction of the xenocrystic phases from the whole rock composition (McSween and Jarosewich, 1983). A parental magma for EETA79001 was also estimated by calculation through parameterization of liquid phase boundaries (Longhi and Pan, 1989). The above-stated three melts for EETA79001 are plotted in Fig. 1.

3.2. *Melts for olivine-phyric shergottite*

Generally speaking, olivine megacrysts in most olivine-phyric shergottites seem to be phenocrysts (Goodrich, 2002), suggesting that the bulk compositions could represent their melts. The whole rock composition of the Y980459 olivine-phyric shergottite represents the parental melt (Ikeda, 2004). In addition, magmatic inclusions in olivine megacrysts in Y980459 give an early-stage melt of the fractional crystallization. The groundmass composition also represents a fractionated melt. Therefore, the three melts for Y980459 are plotted in Fig. 1, although the groundmass was produced by metastable crystallization mainly of pyroxenes and does not represent the stable crystallization product (Ikeda, 2004). Therefore, the groundmass of Y980459 is excluded from the shergottite melt trend (Fig. 1).

Some olivine-phyric shergottites seem to contain cumulus megacrysts; olivine megacrysts for NWA 1068 (Barrat *et al*., 2002) or xenocrystic orthopyroxene megacrysts for DaG 476 and 489 (Wadhwa *et al*., 2001). Therefore, their whole rock compositions do not necessarily represent their melt compositions. The groundmass of NWA1068 is not yet obtained, and the bulk is not plotted here. Modal compositions of xenocrystic orthopyroxene megacrysts in DaG 476 and 489 are less than 4 wt% (Wadhwa *et al*., 2001), indicating that they do not so much contribute to their bulk composition. The groundmass composition of DaG 476 was obtained as a melt (Zipfel *et al*., 2000), and it is plotted in Fig. 1 together with the whole rock compositions of the pair meteorites, DaG476 and 489. A trapped melt was estimated from magmatic inclusions in olivine megacrysts in DaG 735 (Ikeda, 2005), which is a paired meteorite with DaG 476, is also plotted in Fig. 1. Two kinds of trapped melts estimated from magmatic inclusions in olivine megacrysts in SaU 005 (Ikeda, 2005) are plotted in Fig. 1 together with the bulk composition. The bulk composition of Dhofar 019 is also shown in Fig. 1.

3.3. Melts for lherzolitic shergottites

Lherzolitic shergottites are cumulative, and the melts are estimated as intercumulus melts or trapped melts in olivine grains. The intercumulus melt for the ALH-77005 lherzolitic shergottite was obtained by subtraction of cumulus phases from the whole rock composition (Lundberg *et al*., 1990). The trapped melt for the magmatic inclusions in olivines in ALH-77005 was estimated by Ikeda (1998). The two melts for ALH-77005 are plotted in Fig. 1. The trapped melt in olivine in LEW88516 was estimated by Harvey *et al*. (1993), and it is shown in Fig. 1.

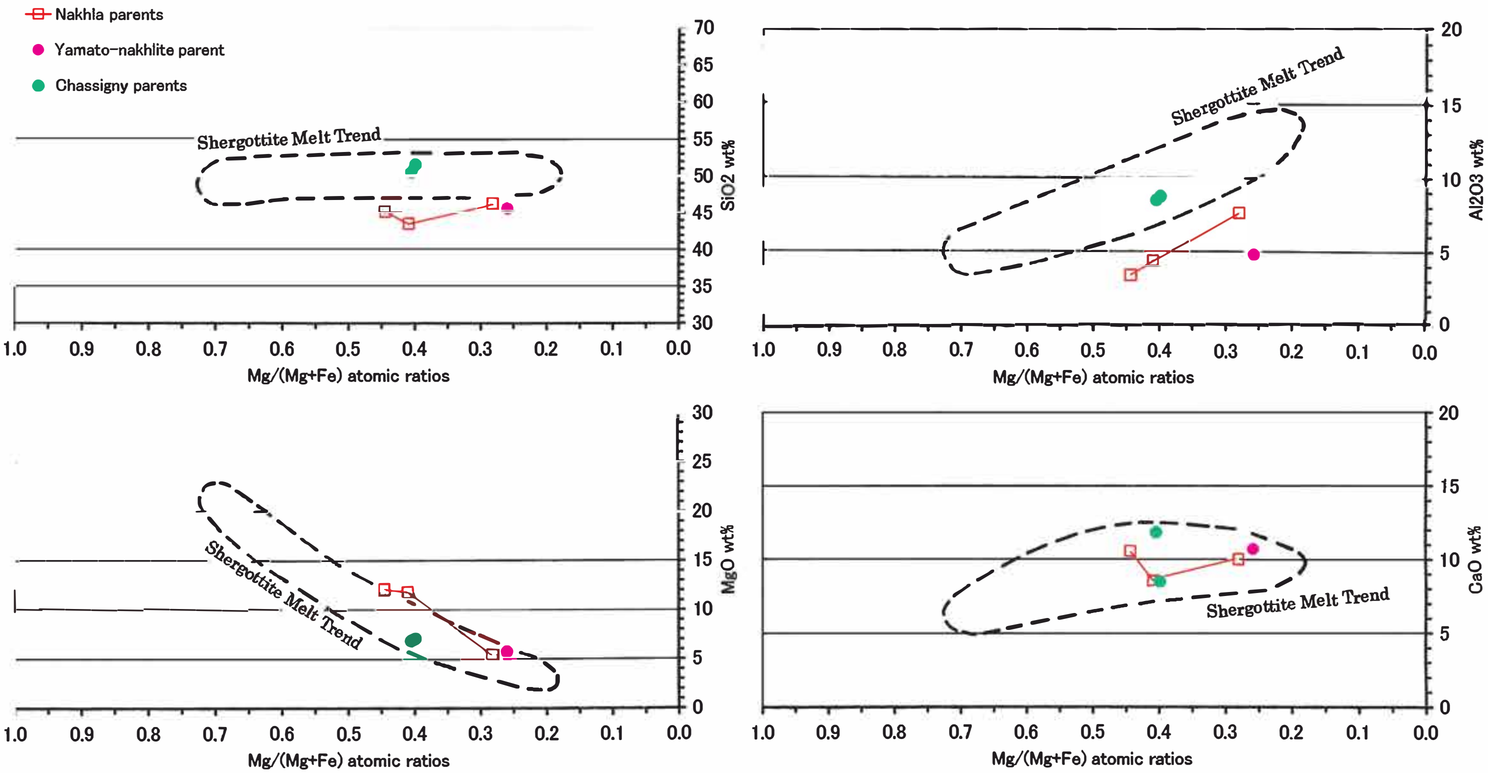
3.4. Assimilation and weathering for the shergottite melt trend

The various redox states for shergottites are interpreted to imply various degrees of interaction between the parent melts and a martian crustal component (Borg *et al*., 1997; Wadhwa, 2001; Jones, 2003). However, the martian crust seems to be mostly basalt-covered world (McSween, 2002) and seems to be lacking in granitic rocks. Therefore, the major-element compositions of the shergottite melt trend may not be so much changed by the assimilation of the martian basaltic crustal components. Alternatively, instead of crustal contamination, Borg and Draper (2003) presented a plum pudding model, where incompatible element-rich components are embedded in depleted mantles. The ratios of the fertile components to the depleted mantles to produce shergottites by partial melting of the mixed mantles seem to be less than 2% (Borg and Draper, 2003), indicating that the effects of the fertile components to the major element compositions of the shergottite melt trend may be small.

Some shergottites seem to have suffered more or less terrestrial or martian weathering (Barrat *et al*., 2001; Baker *et al*., 2000). Especially, glass and whitlockite in shergottites are susceptible to weathering; K contents are introduced in shergottites replacing Na in the glass during terrestrial alteration, and P_2O_5 are easily lost from the shergottites by decomposition of whitlockite during terrestrial weathering. But the major-element compositions of the shergottite melt trend may not be so much affected by the weathering except for K_2O and P_2O_5 contents.

3.5. Summary

The major-element compositions of the melts for all shergottites form a narrow trend. The melts for olivine-phyric shergottites are more magnesian than the basaltic shergottites, suggesting that the basaltic shergottites could be late differentiates of the olivine-phyric shergottites. However, the source materials of shergottites have various isotopic and minor element data (Harper *et al*., 1995; Borg and Draper, 2003; Treiman, 2003), and they differ at least in isotopic compositions from each other. Alternatively, both have derived from source materials similar in major element compositions with different degrees of the partial melting. As their crystallization ages of shergottites range widely from 150 to 600 m.y. (Nyquist *et al*., 2002), the later hypothesis may be


Nakhla parents
Yamato-nakhlite parent
Chassigny parents
Shergottite Melt Trend
SiO2 wt%
Al2O3 wt%
MgO wt%
CaO wt%
Mg/(Mg+Fe) atomic ratios
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
70 65 60 55 50 45 40 35 30
20 15 10 5 0
30 25 20 15 10 5 0
20 15 10 5 0

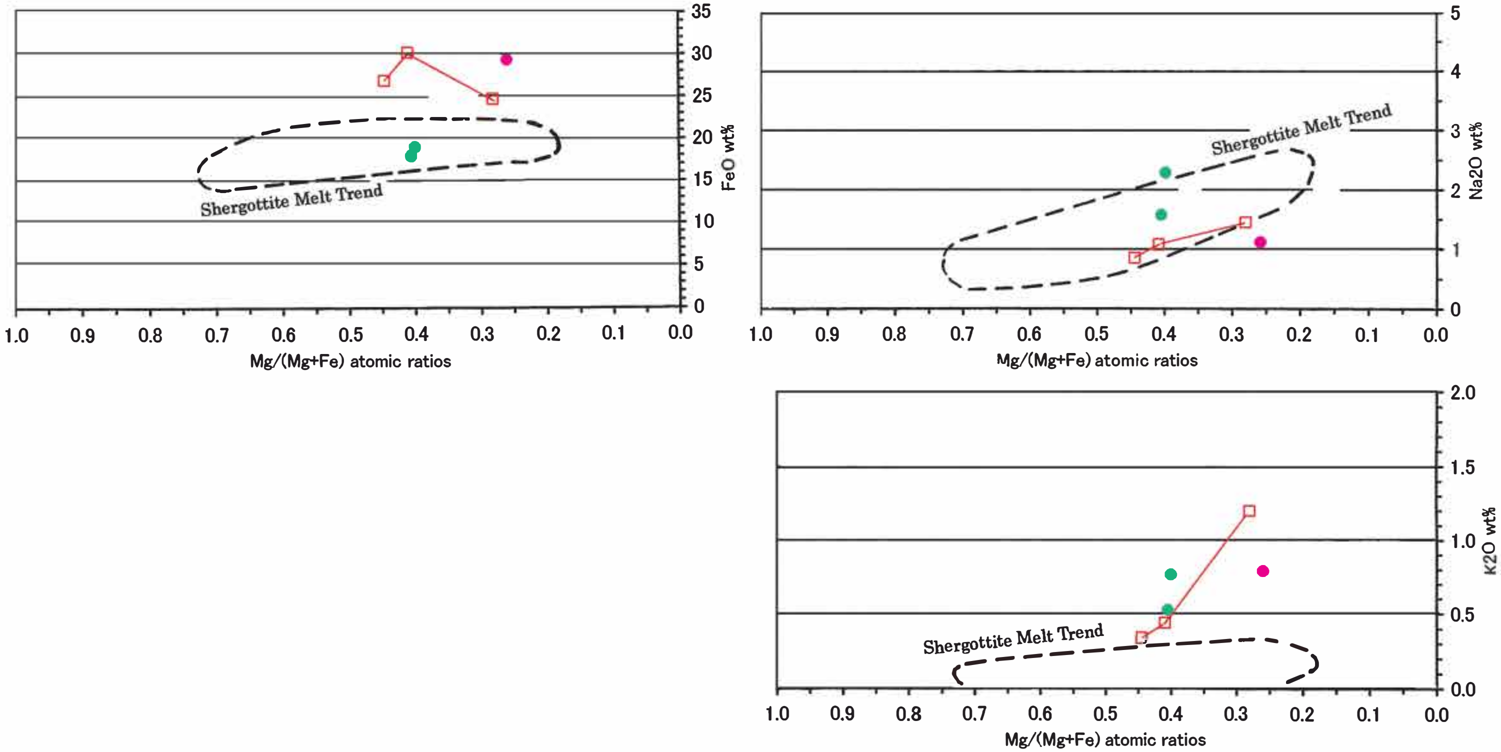
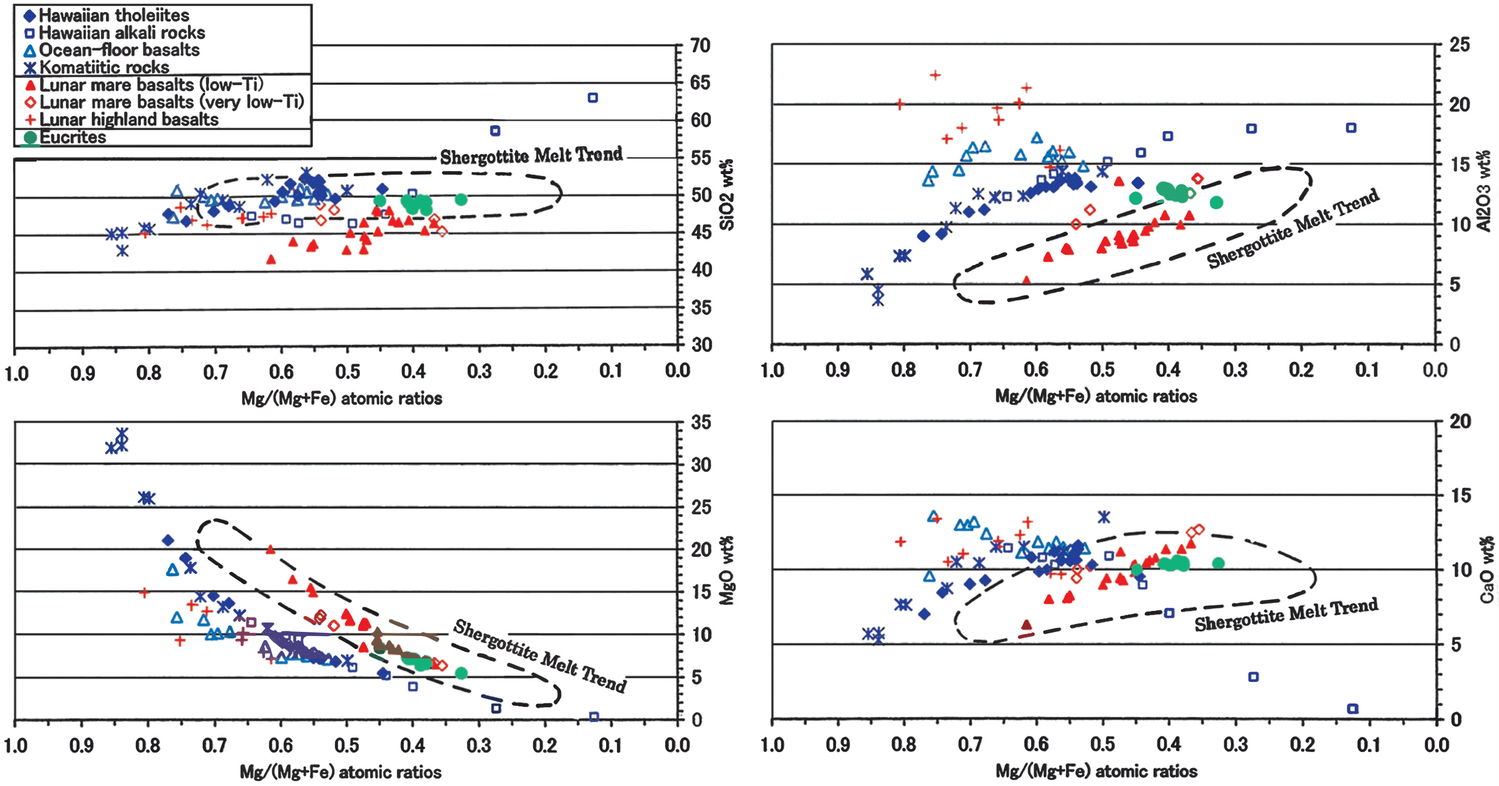


Fig. 2. Melts for nakhlites and chassignite. Nakhlite and chassignite melts are shown by reddish and greenish symbols, respectively. FeO is total irons. P_2O_5 contents of melts for nakhlites and chassignite are not shown here, because they are not yet estimated. Data source are; Harvey McSween (1992) (NIM: nakhlite inclusion median), Treiman (1986) (Nakhla intercumulus melts C D), Imae et al. (2004) (Yamato-nakhlite parental melt), Johnson et al. (1991) (Chassigny melt A), Longhi and Pan (1989) (Chassigny melt Ch).*


Hawaiian tholeiites
Hawaiian alkali rocks
Ocean-floor basalts
Komatiitic rocks
Lunar mare basalts (low-Ti)
Lunar mare basalts (very low-Ti)
Lunar highland basalts
Eucrites
Shergottite Melt Trend
SiO2 wt%
Al2O3 wt%
MgO wt%
CaO wt%
Mg/(Mg+Fe) atomic ratios

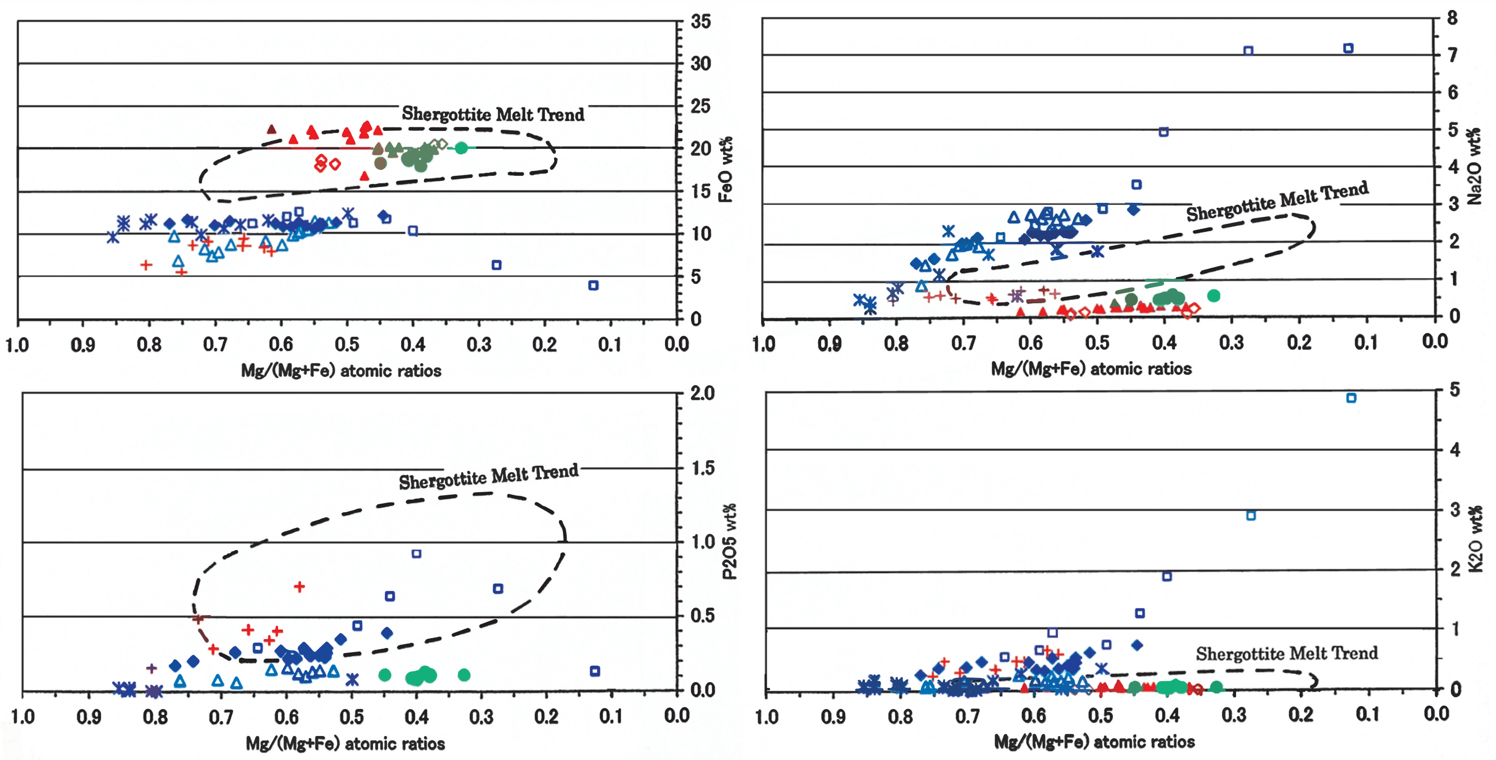


Fig. 3. *Comparison of terrestrial basalts (bluish symbols), lunar basalts (reddish symbols) and eucrites (greenish symbols) to the shergottite melt trend. FeO is total irons. The data are quoted from Basaltic Volcanism Study Project (1981). All of the lunar highland basalts (BVSP, 1981) are actually polymict impact breccia.*

more likely. The lherzolitic shergottites seem to have been produced by melts similar to the olivine-phyric shergottite melts or their differentiates (Gnos *et al*., 2002).

4. Comparison of the nakhlite and chassignite melts with the shergottite melt trend

The nakhlites and chassignite are cumulates. The parental melts are taken to be intercumulus melts, and their chemical compositions are obtained by subtraction of cumulus phases from the whole rock compositions. Alternatively, some olivine crystals in nakhlites and chassignite contain magmatic inclusions, and the parental melts are assumed to be initial trapped melts of magmatic inclusions in olivine grains.

Two intercumulus liquid compositions were estimated for Nakhla (Treiman, 1986; C & D), and the NIM (nakhlite inclusion median) was obtained from magmatic inclusions in nakhlites (Harvey and McSween, 1992). The three melts for nakhlites are plotted in Fig. 2. A parental magma for the Yamato-nakhlites (Y000593, Y000749, Y000802) was estimated by Imae *et al*. (2004) and is shown in Fig. 2. A trapped melt was calculated from the magmatic inclusions in olivine grains in Chassigny (Johnson *et al*., 1991), and a parental magma was calculated from experimental results (Longhi and Pan, 1989). The two melts for Chassigny are plotted in Fig. 2.

The major-element compositions of the parental and early-stage melts for nakhlites and chassignite are compared with the shergottite melt trend. Figure 2 shows that the melts for nakhlites are more depleted in Al_2O_3 and more enriched in FeO and K_2O, indicating that the nakhlite melts do not coincide with the shergottite melt trend. Although most components of melts for chassignite are well coincident with the shergottite melt trend, the K_2O contents of melts for chassignite are higher than those for the shergottite melt trend, suggesting that the chassignite also has a different origin from the shergottites.

5. Comparison of terrestrial basalts, lunar basalts and eucrites with the shergottite melt trend

Generally speaking, the bulk compositions of terrestrial basalts, lunar basalts and eucrites are considered to represent the melts, and their bulk compositions are plotted in Fig. 3. The FeO contents of the shergottite melt trend are high, and the Al_2O_3 contents are low in comparison to terrestrial basalts and komatiites, indicating that the terrestrial rocks are dissimilar to the shergottite melts. Lunar mare basalts with low TiO_2 and eucrites are rather similar to the shergottite melt trend, although their alkali contents are lower than those for the shergottite melt trend. The similarity in major element compositions among lunar mare basalts, eucrites, and shergottite melts supports that the three may have formed by similar planetary processes; they formed from cumulates produced at the floors of primordial magma oceans in the early history. The higher alkali contents for shergottite melts may reflect the larger size of Mars in comparison to Moon and Vesta.

6. Formation of the shergottite melt trend under low-pressure conditions

The parental and fractionated melts for shergottites are plotted in the pseudoternary system of quartz-olivine-plagioclase under a low-pressure (1 bar) condition (Fig. 4a). In Fig. 4a, liquidus field boundaries with mg = 0.562 and An = 77 (Longhi and Pan, 1989) are shown for reference. The parental melts for most olivine-phyric shergottites are plotted in the olivine liquidus field, whereas the parental melts for basaltic shergottites are plotted along the liquidus field boundary between pyroxene and olivine (Fig. 4a). Although one parental melt of lherzolitic shergottites is plotted in olivine liquidus field, the others are plotted along the liquidus phase boundary between olivine and pyroxene. These suggest that shergottite melts were produced by various degrees of partial melting of source materials and have experienced fractional crystallization under a low-pressure condition. Dann *et al*. (2001) concluded that the Shergotty meteorite crystallized under a low pressure (0.56 kb) condition with an assumption that H_2O was saturated in the parental magma. Plume tectonics (Kiefer, 2003; Jones, 2003) may be an important process to drive the partial melts from the source mantle to the martian surface. Probably final separation of the melts from the source materials in the plume took place after intrusion of the plume into shallower depths.

7. Formation of melts for the nakhlites and chassignite under moderate-pressure conditions

The parental melts for nakhlites are plotted in Fig. 4a, and they are poor in quartz components in comparison to the shergottite melts. This indicates that nakhlite melts are produced at a different condition from the shergottite melts. As the source materials of the parental magmas for nakhlites may have contained spinel or garnet instead of plagioclase (Treiman, 1986), the remelting may take place at deeper mantle for nakhlite melts than the melts for shergottites.

The nakhlite and chassignite parent magmas have similar REE patterns to each other, and they may have been generated by minuscule degrees of partial melting of a partly depleted source mantle, although Chassigny seems not to be co-magmatic with nakhlites (Wadhwa and Crozaz, 1995). Therefore, it is likely that both the nakhlite and chassignite melts may have been produced from similar source materials, although they may have fractionated under different conditions. The chassignite contains abundant amount of cumulus olivines, indicating that it crystallized and settled olivine grains abundantly from the original magma. This is consistent with an idea that the chassignite had fractionated at a low-pressure condition to crystallize olivine abundantly. The fractional crystallization trend for the chassignite, which originated from a magma similar to the nakhlite melts, is schematically shown by a green arrow in Fig. 4a.

The invariant point for a garnet peridotite under a 30 kb pressure was obtained by Longhi (1995), and it is shown in Fig. 4b. This indicates that the invariant point for plagioclase peridotite under a 1 bar pressure moves toward the invariant point for the garnet peridotite with increasing pressures. Although the exact points of invariant points for nakhlite melts are not known, melts for nakhlites and chassignite may have

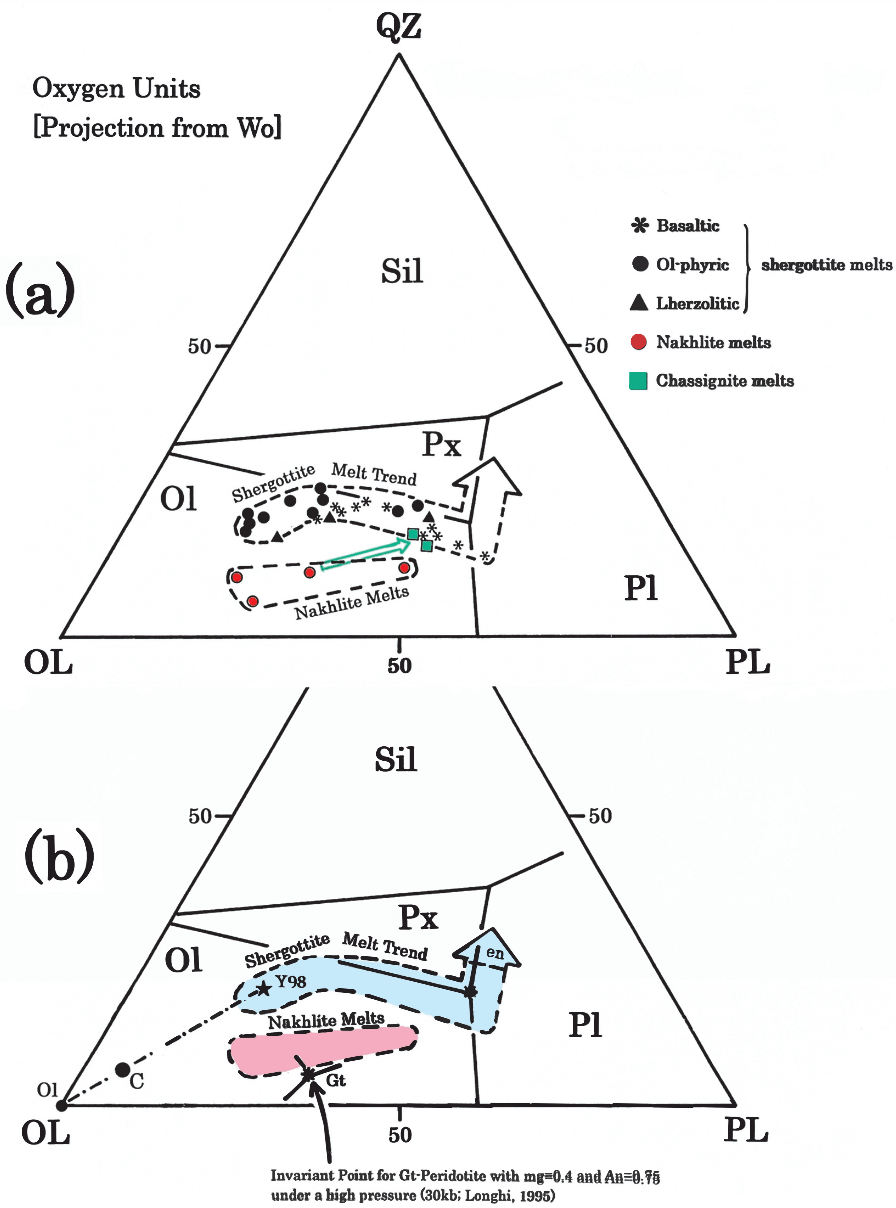


Fig. 4. Phase diagram of pseudoternary system of quartz (QZ)-olivine (OL)-plagioclase (PL). Liquidus field boundaries with mg=0.562 and An=77 are shown by boldlines (Longhi and Pan, 1989). (a) Melts for SNC meteorites are plotted. The shergottite melt trend is shown schematically by a dashed arrow. Nakhlite melts are surrounded by a dashed line. The chassignite melts are plotted near the border of the shergottite melt trend, and a green arrow suggests the fractional crystallization for the chassignite. (b) A plausible source material for olivine-phyric shergottites is shown by a solid circle with C (column C in Table 1). The bulk composition of Y980459 (Y98) is shown by a solid star. Two invariant points at low- and high-pressure conditions are shown by asterisks (see text).

been produced under a moderate pressure between 1–30 kb, under which the liquidus field boundary may locate near the nakhlite melts in Fig. 4b.

The parental melts for both nakhlites and chassignite were produced at moderate pressures, but chassignite melts fractionated at low-pressure conditions, although nakhlite melts did not experience remarkable fractionation at low pressures. Jones (2003) presented a layered mantle model for Mars consisting mainly of deeper nakhlite lherzolitic mantle and shallower shergottite harzburgitic mantle with 50 km-thick crust. A plume rises up from the deeper nakhlite mantle into a shallower zone, and partial melting of the nakhlite source may proceed in the top of the plume. The final separation of the partial melts from the nakhlite source may take place at moderate pressure conditions between 1–30 kb.

8. Source material for olivine-phyric shergottites

Longhi and Pan (1989) proposed a petrogenesis model including common sources for the SNC meteorites; nakhlites and chassignite were produced from Al-poor source materials by the metasomatism and the shergottites were produced by the partial melting of the same source material. According to Harper *et al*. (1995), the Nd isotopic data indicate that the nakhlite and chassignite groups and the shergottite group could not have originated from a common source material. The contamination of crustal materials by the martian magmas seems to make the isotopic and minor-element data difficult to obtain a unique solution for their source materials. However, a wide range of redox states for shergottites seem to need interaction of magmas with crustal components (Wadhwa, 2001).

All SNC meteorites seem to have experienced an early magmatic differentiation (4.51 G.y.) just after the accretion of Mars, where the Sm/Nd, U/Pb, and Rb/Sr ratios have been strongly fractionated (Jagoutz, 1991; Jones, 2003). The fractionation seems to take place in martian magma ocean (Borg and Draper, 2003; Jones, 2003). The decoupling of two isotopic systematics, Rb/Sr and Sm/Nd systems, by the early differentiation in Mars may be attributed to either cumulate or crust formation processes (Borg *et al*., 1997).

The major-element composition of a source material for olivine-phyric shergottites is estimated by the following two constraints. (1) The parental magmas of some olivine-phyric shergottites are the most magnesian and they are situated in the olivine liquidus field of the Ol-Qz-Pl pseudoternary system. Therefore, the composition of the source material should be between the parental magmas for magnesian olivine-phyric shergottites and the olivine residue. (2) EETA79001A contains harzburgitic xenoliths, and the most magnesian mineral is orthopyroxene with mg = 0.84 (McSween and Jarosewich, 1983). The mg of olivine which coexists with the magnesian orthopyroxene is obtained using a partition coefficient of 1.3 between olivine and orthopyroxene (Larimer, 1968) and is Fo_{80}. As the modal ratio of xenocrystic olivine to orthopyroxene is about 3 (McSween and Jarosewich, 1983), the whole rock of the xenolithic harzburgite may have the mg = 0.81. The xenoliths could present a source material for shergottites, and if so, the source mantles should have mg ratios around 0.81.

Plausible source materials for olivine-phyric shergottites are estimated under the above-stated two constraints. The plausible source materials are obtained as mixtures of olivine-phyric shergottite melt and the most magnesian olivine. The Y980459 meteorite was used for the olivine-phyric shergottites, because the bulk composition represents the magnesian parental melt (Ikeda, 2004). The relic olivine is taken to be the most magnesian phenocrystic olivine in olivine-phyric shergottites (Fo_{84} in Y980459).

The plausible source materials for olivine-phyric shergottites are obtained as mixtures of Y-98 and olivine (Fo_{84}). Their mixing ratios are taken to be 1 : 9, 2 : 8, 3 : 7, 4 : 6, and 5 : 5, which are shown in Table 1. Among them, mg of a source material with 3 : 7 has 0.81 (Table 1), and the source material C is the most likely for olivine-phyric shergottites. The 30% partial melting of the source C may give rise to the magnesian olivine-phyric shergottites, and is plotted in Fig. 4b. It depleted in Al_2O_3, CaO, Na_2O, and K_2O in comparison to martian mantle (+crust; Wänke and Dreibus, 1988) and may be cumulative mantles which have formed in the magma ocean with separation of incompatible element-rich crustal components.

The parental melts for various shergottites may be produced by various partial melting degrees of the source materials similar in major element composition to the C material , probably less than 30%.

Table 1. Plausible compositions (A, B, C, D, and E) of source materials for olivine-phyric shergottites are represented by mixtures of Y980459 parent melt (Y98 whole rock composition) and its magnesian olivine (Fo_{84}) in wt ratios of 1 : 9, 2 : 8, 3 : 7, 4 : 6, and 5 : 5, which correspond to partial melting degrees of 10%, 20%, 30%, 40%, and 50%. The C composition is the most likely (see text). The martian mantle (+crust; Wänke and Dreibus, 1988) is shown for reference.

	A	B	C	D	E	Mars mantle
Melting degree	10%	20%	30%	40%	50%	
SiO_2	40.77	41.65	42.53	43.41	44.30	44.4
TiO_2	0.05	0.11	0.16	0.22	0.27	0.14
Al_2O_3	0.53	1.05	1.58	2.11	2.64	3.02
Cr_2O_3	0.45	0.48	0.51	0.54	0.57	0.76
FeO	14.94	15.21	15.47	15.74	16.00	17.9
MnO	0.29	0.31	0.34	0.36	0.39	0.46
MgO	41.78	39.32	36.85	34.39	31.93	30.2
CaO	0.74	1.36	1.99	2.61	3.24	2.45
Na_2O	0.05	0.10	0.14	0.19	0.24	0.50
K_2O	0.00	0.00	0.01	0.01	0.01	0.04
P_2O_5	0.03	0.06	0.09	0.12	0.15	0.16
FeS	0.03	0.05	0.08	0.10	0.13	
Total	99.64	99.66	99.75	99.80	99.85	100.03
Mg#	0.83	0.82	0.81	0.80	0.78	0.75

9. Conclusions

(1) Melts for all shergottites including olivine-phyric, basaltic, and lherzolitic shergottites form a major-element trend (the shergottite melt trend).

(2) The shergottite melt trend differs from the trends for terrestrial basalts, but similar in major element compositions to lunar basalts and eucrites except alkali and P_2O_5 contents, supporting that shergottite melts were produced by planetary processes similar to Moon and Vesta.

(3) The nakhlite and chassignite melts are different from the shergottite melt trend.

(4) The melts for shergottites may have formed under low-pressure conditions, whereas the nakhlite and chassignite melts seem to have been produced under moderate pressures between 1 and 30 kb.

(5) The chassignite melts may have experienced fractional crystallization under low-pressure conditions, but the nakhlite melts did not.

(6) A plausible source material for olivine-phyric shergottites is an alkali-poor depleted lherzolitic peridotite with the mg ratio of 0.81.

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