Petrogenesis of Parent Magmas of SNC Meteorites[1]

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Abstract—Primary magmas for the investigated SNC meteorites have been estimated on the basis of the bulk compositions of "basaltic shergottites" and melt inclusion data for other SNCs. All estimated compositions are similar in terms of major elements. These compositions are high in Mg + Fe and Si mole fractions, and they are similar in this respect to terrestrial boninites.These primary magma compositions could only have been produced by small degree partial melting of an olivine-rich source, which could be related to the Martian primitive mantle either by previous episodes of the extraction of basaltic melts, which formed a very thick crust, or by formation of olivine-rich cumulates during the consolidation of primordial magma ocean, which originally had the composition of the Martian primitive mantle (similar to terrestrial pyrolite, but with significantly higher Fe/Mg ratio).The estimated contents of heat producing elements in this olivine-rich source are very low, and they are likely to be not sufficient to provide energy for magma genesis, if the whole of the Martian mantle now consists of such very depleted harzburgite.The hypothesis is favored that assumes primitive magma generation in the olivine-rich cumulate pile, originally formed during the consolidation of the primordial global magma ocean. The solidified layer of residual melt, which underlay the olivine-rich cumulate pile, may be enriched in incompatible elements, including K, U, and Th, whose radioactive decay might have provided heat for the initiation of plumes in which primary magmas of SNC meteorites originated at higher levels. This scenario is consistent with trace element and isotope data, which provide evidence that the Martian mantle retains geochemical heterogeneities from the earliest stages of its history resulting from an early isolation of, and subsequent inefficient mixing between, different mantle reservoirs in Mars.

INTRODUCTION

The SNC meteorites (named after Shergotty, Nakhla and Chassigny) differ from other differentiated meteorites in their isotopic and trace element characteristics. Their young radiometric ages first observed for Shergotty [1] were the first lines of evidence in support of their origin on a planetary-sized body, probably Mars [2, 3]. Later, these young ages for the crystallization of SNC meteorites were confirmed by a number of methods [4]. The most convincing evidence for the origin of these rocks on Mars is provided by the isotopic composition of the trapped gases in shock-melted glass in shergottites, which was demonstrated to be indistinguishable from the Martian atmosphere as measured by mass spectrometer on board the *Viking* lander [5–7]. The recognition of shergottites as fragments of Martian magmatic rocks permitted estimating the bulk composition of the silicate part of Mars on the basis of the geochemical analyses of SNC meteorites using the general principles of element behavior in terrestrial magmatic systems and the regularities governing the composition of chondritic meteorites [8–12]. These estimates are also broadly consistent with the data

provided by Earth-based and orbital spectra, and *in situ* spectral and chemical observations from the *Viking* and *Pathfinder* landers [13, 14]. The estimated composition of the Martian primitive mantle provided foundations for the interpretation of other geochemical and geophysical data emerging for Mars during the last few years.

It has been noted that the composition of the immediate mantle source(s) of the parental magmas for SNC meteorites must differ significantly from undifferentiated primitive lherzolites such as Wänke–Dreibus model composition [15–17], and it allows one to assess the processes and scale of the global differentiation of Mars. The calculated compositions of the primary melts of SNC meteorites allow one to estimate P–T conditions of their generation, providing insight into the thermodynamic parameters of Martian interiors.

Previously, such estimations were done for Shergotty and Zagami [17] basaltic shergottites, for which petrological and geochemical data had long since been available. In this paper, we consider all the published data on the composition of intercumulus melts and melt inclusions in SNC meteorites. This has been done in order to test the possibility that the composition of the mantle sources and parameters of the magma generation process may be different for various groups of SNC meteorites.

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[1] This article was submitted by the authors in English

Table 1. Parent melts of various SNC meteorites

	1	2	3	4	5	6
SiO_2	49.359	51.726	49.385	48.407	47.589	50.058
TiO_2	0.757	0.525	0.678	0.665	1.103	0.694
Al_2O_3	6.247	5.974	5.183	5.408	6.085	6.347
FeO	18.657	17.281	18.464	19.638	19.861	18.806
MgO	15.739	14.573	15.577	16.565	16.755	15.864
CaO	7.722	7.488	8.960	7.649	5.925	7.220
Na_2O	0.941	0.701	1.080	0.987	1.598	0.912
K_2O	0.058	0.053	0.109	0.122	0.537	0.099
MnO	0.518		0.563	0.544	0.547	

Note: 1—Parent melt estimated as the matrix between xenocrysts of olivine, orthopyroxene, and chromite in the lithology A of meteorite EETA 79001 [19] recalculated to equilibrium with olivine Fo_{82} (slightly more magnesian than in the original publication). 2—Primary magma calculated from the bulk composition of Dar al Gani 476 [24] assuming that it is in equilibrium with homogeneous grains of olivine Fo_{82}. 3—Primary magma calculated from Zagami bulk composition [25] by fractional addition of equilibrium olivine, assuming its composition in the mantle source as Fo_{82}. 4—Similar calculations for the bulk composition of Shergotty [8]. 5—Similar calculations for the melt trapped as microinclusions in cumulus olivine in Chassigny [20]. 6—Similar calculations for the bulk composition of Dhofar 019 [23]. In all cases K_d(Mg/Fe) for olivine – melt equilibria was assumed to be 0.33.

EVALUATION OF PRIMARY MAGMA COMPOSITIONS

All SNC meteorites consist of varying proportions of phenocrysts (or cumulus minerals) and products of crystallization of intergranular melt. Detailed petrographic investigations allowed one to estimate compositions of intercumulus melts for a number of SNC meteorites [18, 19] partly based on the analyses of melt inclusions [20, 21]. For the melts that are in equilibrium with olivine (or nearly in equilibrium), compositions of primary magmas may be approximately estimated by the fractional addition of equilibrium olivine until its Mg-number is high enough to be compatible with the model composition of the Martian mantle.

One of two lithologies of EETA 79001 contains zoned megacrysts of olivine and orthopyroxene (presumably, disaggregated xenoliths of harzburgite) with Mg-numbers in the cores up to 84 [19]. The groundmass of lithology A, which, it has been suggested, reflects parental melt composition [19], corresponds to equilibrium with olivine Fo_{81} (assuming that K_d(Fe/Mg) = 0.33). This is higher than the Mg-number of the estimated primitive Martian mantle [11], and therefore this composition may be accepted as one of the Martian primary magmas (Table 1).

Dar al Gani 476 is a rock composed of olivine megacrysts (about 24 vol %) set in a fine-grained groundmass of pyroxene and maskelynitized plagioclase. The most magnesian cores of olivine megacrysts are Fo_{79}, and assuming that originally homogeneous grains of this composition were immersed into equilibrium melt, we may estimate the composition of this hypothetical melt by subtracting olivine from bulk composition, which yields about 11% MgO, 16% FeO, and 53% SiO_2.

In this case, however, the calculated amount of olivine phenocrysts would be about 36%, which is much larger by comparison with the observed value. Assuming that originally olivine phenocrysts were more magnesian but later changed their composition due to exchange with the residual melt or crystalline phases in intercumulus matrix and intracrystalline diffusion of divalent cations, the calculations would yield a lower proportion of olivine phenocrysts. At an olivine composition with Fo_{82} (similar to that which should be in equilibrium with the melt of matrix in EETA 79001, see above), this value would be 27 wt %, which is sufficiently close to the measured proportion of this phase. We, therefore, have chosen olivine of this composition to estimate the parent magma for Dar al Gani 476 meteorite, which would contain 51.7% SiO_2 and 14.6% MgO (Table 1).

Shergotti and Zagami do not contain olivine among early minerals, but experiments with Zagami composition showed that olivine ($Fo_{75.8}$) appears at the liquidus together with pigeonite [22]. It implies that the parent magma of this meteorite was close to olivine saturation. The same probably applies to Shergotty bulk composition and its estimated intercumulus melt, because these compositions are fairly similar to Zagami. Chassigny is a dunitic cumulate containing Fo_{68} olivine, and, therefore, its parent melt assessed from melt inclusion studies [20] was undoubtedly saturated with respect to olivine. Shergottite Dhofar 019 also represents olivine saturated magma, because it contains zoned olivine grains with cores approaching Fo_{60} [23]. We, therefore, may estimate primary melt compositions for these four meteorites using a numerical procedure that models fractional addition of equilibrium olivine to the initial
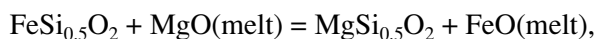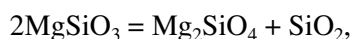
melt until the olivine Mg-number becomes identical with that of the assumed mantle source (reverse to fractional crystallization of olivine). For this we have assumed that olivine in peridotitic source contains 82% of forsterite (same as for Dar al Gani 476). We have also recalculated the composition of the matrix in lithology A of EETA 79001 (see above) assuming equilibrium with olivine Fo_{82}. The results of these calculations are given in Table 1.

Addition of olivine to the initial melt is obviously an oversimplification, inasmuch as in reality some other minerals (most likely, low-Ca pyroxene) could have crystallized to some extent together with olivine. If low-Ca pyroxene indeed precipitated in addition to olivine, then SiO_2 contents in primary melts would be somewhat higher than those in Table 1.

NUMERICAL MODELING OF PERIDOTITE ANATEXIS

The existing programs that allow one to model subliquidus equilibria in multicomponent silicate systems are not specifically calibrated for compositions similar to Martian meteorites, and their application to modeling the crystallization of Martian magmas confronts serious difficulties [13]. It concerns first of all the advanced stages of fractional crystallization, when several solid solution series (e.g. two pyroxenes, plagioclase and Fe–Ti oxides precipitate simultaneously). It may be expected that for the simpler phase assemblages, including only melt, olivine, and low-Ca pyroxene, numerical modeling may be more reliable, because thermodynamic properties of these solid solutions are relatively simple, and their equilibria with melt are well investigated experimentally.

We have collected a data base of experimentally investigated equilibria among melt, olivine, and orthopyroxene with melts containing more than 12 wt % of FeO (total), because these compositions are closer to Martian meteorites and soils by comparison with the majority of terrestrial magmas. Regression analysis of these data allow one to estimate temperature and pressure dependences of the equilibrium constants of the reactions

$$2MgSiO_3 = Mg_2SiO_4 + SiO_2,$$

$$Mg_2SiO_4 = MgSiO_3 + MgO,$$

$$FeSi_{0.5}O_2 + MgO(melt) = MgSi_{0.5}O_2 + FeO(melt),$$

and of partition coefficients of Al, Ca, and Ti between orthopyroxene and melt. These data, together with the mass balance equations and the constraints imposed by stoichiometry and the charge balance of solid solutions, were used to calculate compositions of coexisting phases for the melting of hypothetical Martian mantle rocks at various temperatures and pressures utilizing the PARMEL program [26, 27]. Parallel calculations with the MELTS package [28] yielded melt composi-

tions similar to those calculated by PARMEL (see examples in the next section).

CONSTRAINTS ON PRESSURE OF MAGMA GENESIS AND SOURCE COMPOSITION

The Al/Ca and Al/Ti ratios in Martian meteorites are considerably lower than chondritic values and also lower than these ratios in terrestrial basalts. It implies that primitive Martian magmas cannot be melted out from the primitive mantle of this planet, and it has been suggested that, soon after the accretion of Mars, garnet has been lost from a large portion of Martian mantle (this may have happened due to the sinking of garnet-rich cumulates in the postaccretional magma ocean), and this Al-deficient material is the source of magmas during the later epochs. To test the hypothesis that primary Martian magmas may be generated from the peridotites of such composition, we calculated compositions of melts with ca 15.5% MgO (close to the MgO contents in primary magmas estimated for equilibrium with olivine Fo_{82}, Table 1), which may be derived from Wänke–Dreibus primitive mantle composition [11] minus 5% of pyrope-rich garnet (the composition of this garnet was estimated by the PARMEL program for near-solidus conditions for primitive mantle bulk composition). Partial melting was modeled by the PARMEL [26, 27] and MELTS [28] computer programs. The SiO_2 contents of partial melts and degrees of melting are shown as the functions of pressure in Fig. 1. It can be seen that the results of calculations by two numerical methods for H_2O-free conditions are in satisfactory agreement. The addition of water (H_2O contents in the melts from peridotite with initial 0.5% H_2O are in the range of 1.2–1.6%) results in an increase in silica content in the liquid phase. These results also imply that the primary melts of estimated compositions with ca. 50% SiO_2 (Table 1) may be generated only at rather low pressures and at high degrees of partial melting. Isobaric partial melting with more than 20% of the liquid phase is not a realistic mechanism of magma generation, because the amount of intergranular melt may not exceed several percent; otherwise the system would be mechanically unstable. Most likely, high bulk degrees of partial melting may be attained by a near fractional polybaric process during the adiabatic decompression of rising protolith. For Mars this problem was discussed in detail elsewhere [17]. It can be roughly estimated that adiabatic decompression by 0.1 GPa may result in the generation of 0.6–0.7% of partial melt, and, therefore, in order to produce 30% of melt by such a process, we have to start melting from ca. 5 GPa. In this case, a substantial proportion of instantaneous melts even in the presence of water have low SiO_2 contents, and, therefore, this value in the composite melt (mixture of melt portions from various depths of melting column in magma chamber) is much lower than ca. 50% estimated for the primary magmas (Table 1). It implies that such melts could have been produced not from a starting
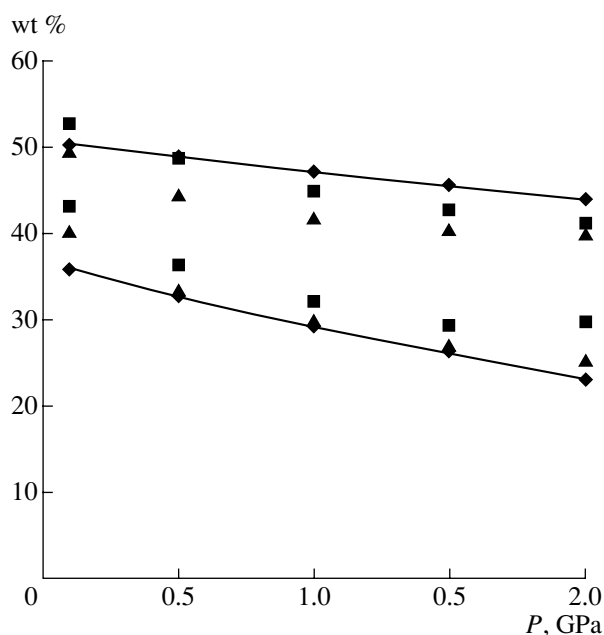
Fig. 1. SiO_2 contents (upper group of points and line) and fractions of melt (lower group) as functions of pressure calculated for the partial melting of Martian primitive mantle [12] minus 5% garnet composition by the PARMEL computer program (lines with rhombs) and by the MELTS computer program (triangles for dry conditions and squares for 0.5% H_2O in the source). MgO contents in melt are 15.5 wt %.
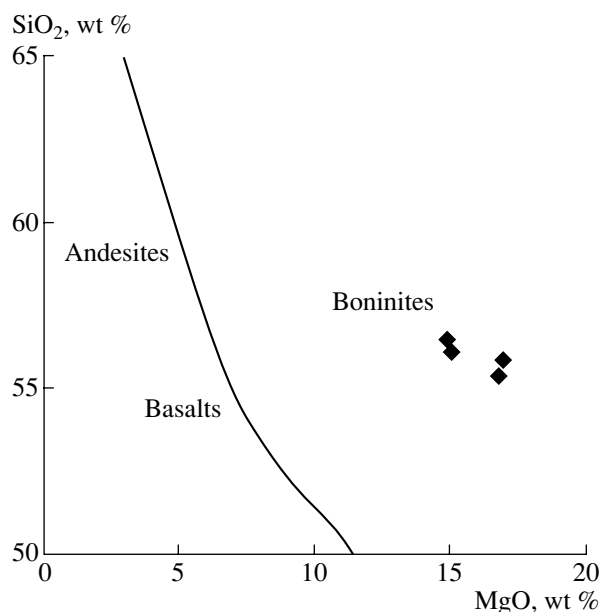

Fig. 2. Compositions of Zagami, Shergotty, Dhofar 019 and estimated parent melt of E 79001 recalculated to Mg/(Mg + Fe) = 0.7 (typical for primitive terrestrial basalts) plotted on the MgO–SiO_2 diagram with the boundary separating basalts and andesites from boninites [35].

composition similar to the primitive mantle but from material much richer in olivine. This can be either mantle peridotite that has lost large amounts of "basaltic" components during the previous episodes of magma generation or olivine cumulate formed in postaccretional magma ocean at the depth of density crossover (about 600 km for Mars—above this level olivine is denser than melt, and below this level melt is denser by comparison with olivine [29, 30]).

The compositions of primitive "basaltic" shergottites are characterized by high MgO + FeO contents at elevated values of SiO_2 mole fractions. These features make them similar to terrestrial boninites. To illustrate this similarity, we recalculated bulk compositions of Shergotty [8], Zagami [25], Dhofar 019 [23], and the matrix between xenocrysts in lithology A of E 79001 [19], changing Mg-numbers to 70, a typical value of terrestrial primitive magmas. Recalculated values of MgO contents range between 14.9 and 16.8 wt % at SiO_2 above 55 wt %, deep inside the boninite field on the MgO–SiO_2 diagram (Fig. 2). Previously, the similarity to boninites has been noted for Shergotty and Zagami bulk compositions [17] and for melts trapped as microinclusions in the cumulus olivine grains in Chassigny [20].Terrestrial boninites are thought to have originated by the melting of olivine-rich refractory rocks, harzburgites, which appeared due to the loss of basaltic melt from fertile lherzolites during the previous episodes of partial melting [31]. In the majority of cases, typical boninites are formed in the shallow upper man-

tle under hydrous conditions due to the second stage anatexis of recently subducted (and therefore hot) oceanic lithosphere rich in harzburgites triggered by the influx of volatile components in the environment of the subduction zone. Water plays an important role in this process, because in its presence olivine + low-Ca pyroxene cotectic is shifted towards more siliceous compositions. It may be noticed in this respect that the presence of water in Martian magmas has been advocated in a number of recent works [20, 22, 32, 33]. On the other hand, some terrestrial boninitic magmas are probably formed in equilibrium with harzburgitic crystalline restite in the shallow upper mantle (below 0.5 GPa) under anhydrous conditions [34, 35].

In order to perform very approximate modeling of olivine-rich source compositions of Martian primary magmas, we have calculated the composition of the melt that would be in equilibrium with olivine Fo_{80} for the bulk composition of Wänke–Dreibus primitive mantle minus 5% garnet and then mixed 10% of this melt with 90% of olivine (olivine cumulate with intercumulus melt, composition 1 in Table 2). This fraction of intercumulus melt is typical of the rocks of layered intrusions [36]. Alternatively, we calculated the composition of harzburgitic restite produced by the melting of Wänke–Dreibus primitive mantle minus 5% garnet with the addition of 1% melt (composition 2 in Table 2).

As can be seen from Table 2, both model compositions of the source material of shergottitic magmas are

Table 2. Compositions of the source material of shergottitic magmas and their partial melts

	1	2	3	4	5
SiO$_2$	40.786	46.893	49.848	49.368	49.359
TiO$_2$	0.029	0.016	0.402	0.426	0.757
Al$_2$O$_3$	0.396	0.220	5.592	6.434	6.247
FeO*	17.319	15.509	19.497	19.598	18.657
MgO	40.819	37.022	15.531	15.325	15.739
CaO	0.523	0.324	7.196	8.185	7.722
Na$_2$O	0.120	0.014	1.794	0.615	0.941
K$_2$O	0.009	0.001	0.14	0.048	0.058
Melt fraction			6.698	2.349	

Note: 1—90% Fo_{82} + 10% intergranular melt from Wänke-Dreibus primitive mantle minus 5% garnet. 2—Residual harzburgite from melting of Wänke-Dreibus primitive mantle minus 5% garnet at 0.5 GPa and 1410°C with the addition of 1% of melt. 3—Partial melt of (1) at 0.3 GPa and 1370°C (PARMEL program). 4—Partial melt of (2) at 0.3 GPa and 1370°C (PARMEL program). 5—Primary magma recalculated for equilibrium with olivine Fo_{82} from the composition of the matrix between xenocrysts in lithology A of meteorite EETA 79001 (Table 1).

broadly similar, and simulation of their partial melting produces compositions similar to estimated primary melt linked to EETA 79001 bulk composition.

FRACTIONAL CRYSTALLIZATION OF SHERGOTTITIC MAGMAS

Comparison of the estimated compositions of primary magmas with the compositions of intercumulus melts and bulk compositions of more evolved shergottites allows one to test the assumption of their derivation from similar primitive melts and to assess the general features of their differentiation during the crystallization in crustal magma chambers. Compositions of basaltic shergottites (Shergotty, Zagami, DAG 476, EETA B, Los Angeles, QUE 94201, and the matrix between xenocrysts in lithology A of E79001), melt compositions estimated from the data on melt inclusions (Chassigny and Nakhla), and MPSFR (Mars Pathfinder soil-free rock [14]), together with the estimated trend of crystallization differentiation for primary magma for Zagami bulk composition, were plotted on triangular cation fraction diagrams Ca–(Mg + Fe)–Al and Si–(Mg + Fe)–(Ca + Al) (Fig. 3). All olivines irrespective of Mg-numbers plot on these triangles into the same points, and, therefore, olivine control lines (compositional trends of magmas or magmatic cumulates, caused by the crystallization of olivine as the only solid phase) are straight lines emanating from the points of olivine composition. The trend of crystallization differentiation of the estimated primary melt for Zagami bulk composition consists of a short straight line connecting points of the primary melt (calculated for equilibrium with olivine Fo_{80}, Table 1) and bulk composition of Zagami, and for a less magnesian composition it is shown according to experimental data for equilibrium crystallization of Zagami composition at 1 bar pressure and QFM oxygen fugacity [37].

It can be seen from Fig. 3 that the composition of DAG 476 plots closest to the olivine point, which agrees with the petrographic studies showing that this rock is olivine cumulate with a substantial proportion of intercumulus melt [24]. The matrix between xenocrysts in lithology A of E79001 is the next most magnesian among the plotted compositions, and it plots not very far from the estimated Zagami primary magma. It is not excluded that matrix of E79001 may correspond to one of the primary magmas of shergottitic rocks. Bulk composition of Dhofar 019 also plots very close to the matrix of EETA 79001, and it is another candidate for the sample of primary melt. All the other points, including the projection of MPSFR, are situated in the vicinity of the estimated trend of crystallization differentiation. It implies that all of them may be derivatives of a series of primary magmas of similar compositions. As has been mentioned above, Si and (Mg + Fe) mole fractions in these compositions are similar to terrestrial boninites, their generation requires olivine-rich harzburgitic source, and partial melting must proceed at relatively low pressures, possibly in the presence of moderate amounts of water.

Two points correspond to the residual glasses in the matrices [38] or melt inclusions [39] from SNC meteorites (points with the lowest Mg + Fe content). These points lie on the continuation of the trend defined by the SNC meteorite and MPSFR, and this implies that very siliceous melts (much more SiO$_2$-rich even in comparison with MPSFR) may be produced at the late stages of the fractional crystallization of SNC parent magmas.
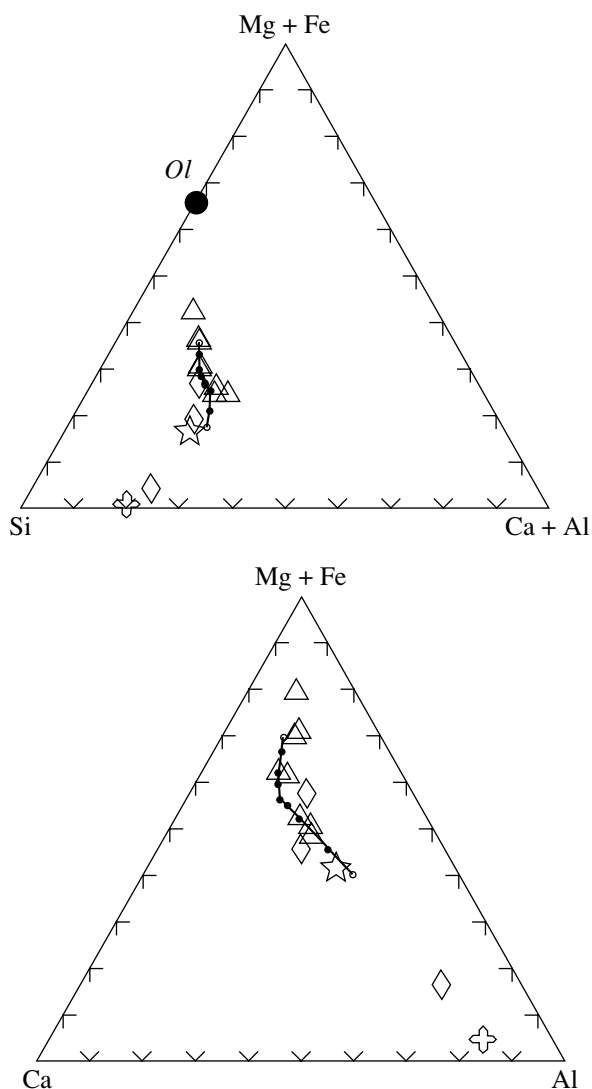
Fig. 3. Compositions of basaltic shergottites (triangles; ordered by decreasing Mg + Fe fraction: Dar al Gani 476, Dhofar 019, matrix in lithology A of E 79001, Zagami, Shergotty, EETA B, QUE 94201, Los Angeles), melt inclusions (rhombs; ordered by decreasing Mg + Fe fraction: Chassigny [20], average of homogenized inclusions in Nakhla [39], average of residual glasses in nonhomogenized inclusions in Nakhla [39]), Pathfinder soil-free rock (star; [14]), residual glass in matrix of Shergotty (cross; [38]), and trend of crystallization differentiation of primary magma for Zagami bulk composition (solid line) plotted on cation fraction triangular diagrams.

HEAT PRODUCING ELEMENTS IN THE SOURCE OF SHERGOTTITIC MAGMAS AND THE POSSIBILITY OF COMPOSITIONAL ZONING IN THE MARTIAN MANTLE

The estimated proportions of liquid phase for the fractional crystallization process resulting in the formation of shergottitic melts from the respective primary magmas together with the estimated fractions of melt for the partial melting of olivine-rich sources, which lead to the formation of primary magmas, allow one to calculate contents of incompatible elements in the source material from their measured concentrations in meteorites. These data are particularly important for heat producing elements: K, U, and Th. Potassium contents in the source of shergottitic magmas estimated from the compositions of intercumulus melts and data from melt inclusions for Shergotty, Zagami, E79001, and the matrix of lithology A of E79001 range between 9 and 65 ppm. From the K/U ratio in the Martian primitive mantle [9, 11, 12] and from chondritic Th/U ratio, concentrations of uranium range between 0.6 and 4 ppb and concentrations of Th between 2 and 14 ppb. The lower limits of these ranges are likely to be more representative due to the risk of crustal contamination.

It has been noted above that all the available information about the compositions of magmas that produced SNC meteorites and possibly also MPSFR, which includes data for bulk rocks, intercumulus matrices, and melt inclusions, may be interpreted as an indication that the source of their primary magmas was very refractory and much richer in olivine in comparison with fertile lherzolites. It may be therefore assumed that the entire Martian mantle consists of this harzburgitic material, whereas a major part of the basaltic components and incompatible elements was transferred into the Martian crust. In this case, however, because of very low concentrations of K, U, and Th in such rocks, heat production inside the Martian mantle would be too low to explain magma genesis in this planet. Therefore, the layered model of the Martian mantle with the preservation of olivine cumulates at depths near 600 km, which are inherited from postaccretional global magma ocean, seems to be more preferable. In this case, one may expect that the heat from radioactive decay comes from horizons deeper than 600 km built up from the crystallized melt of the ancient magma ocean. This material may contain concentrations of incompatible elements including K, U, and Th higher than in the primitive mantle, because they must have accumulated in the liquid phase during the crystallization of olivine, garnet, and possibly some other minerals. Thus, we may hypothesize that the heating from below of olivine-rich layer situated at the depth of ca. 600 km would create rising plumes, which would start to melt on decompression and produce magmas, whose solidification in the crust would lead to the appearance of rocks sampled by SNC meteorites and possibly also the material with the composition of soil-free Pathfinder rocks. Although the mantle enriched with incompatible elements below 600 km would also be heated by radioactive heat, it may not produce plumes reaching the upper parts of Mars, because these rocks due to the elevated amounts of garnet in them should be significantly denser than the overlying olivine-rich material. Recently, a similar model of the formation of plumes in the terrestrial lower mantle has been proposed [40], which invokes heating from below due to the existence of the compositionally distinct lowermost layer

enriched with incompatible elements above the Earth's core.

FORMATION OF OLIVINE-RICH CUMULATES IN GLOBAL MAGMA OCEAN

The global ocean scenario with the subsequent partial melting of cumulate pile is not only consistent with the petrochemical characteristics of the parent magmas of SNC meteorites and compositions of MPSFR and Martian soils, but also capable of explaining the ^{143}Nd, ^{142}Nd, Hf, Os, and Sr isotopic systematics of SNCs ([41–43]. Similar models were also used to account for the siderophile element behavior in SNC meteorites [44, 45]. Available experimental data on the high pressure phase relations in Martian [29, 46–51] and terrestrial [52, 53] primitive mantle compositions, the composition of carbonaceous chondrites [54], and the data for the fundamental boundary system MgO–SiO$_2$ [55, 56] allow one to assess to a first approximation phase transitions during the solidification of the primordial Martian magma ocean.

Assuming that the silicate part of Mars was initially completely molten, the first crystals, which should precipitate at the core–mantle boundary would be either ferropericlase or Mg-silicate perovskite, depending upon the composition of the cotectic at pressures close to 25 GPa (more likely, ferropericlase [57]). The cotectic in the binary system MgO–SiO$_2$ at ca. 23 GPa is situated very close to the projection of the primitive mantle composition [56], and, therefore, relatively soon after the beginning of silicate crystallization, both ferropericlase and Mg-perovskite will precipitate in cotectic proportion, which at the beginning would be close to 15–20% of ferropericlase [56, 58]; but with increasing thickness of the near bottom cumulate pile and decreasing pressure of crystallization, it would be shifted toward lower ferropericlase fractions. After the thickness of the cumulate pile reaches ca. 150 km and the near bottom pressure drops to ca. 22 GPa, two solid-state reactions would reach the near liquidus region simultaneously: first, the production of ringwoodite (Mg–Fe orthosilicate with spinel structure) at the expense of Mg-perovskite and ferropericlase:

$$(Mg,Fe)SiO_3 \text{ (perovskite structure)}$$
$$+ (Mg,Fe)O \text{ (ferropericlase)}$$
$$= (Mg,Fe)_2SiO_4 \text{ (spinel structure)}$$
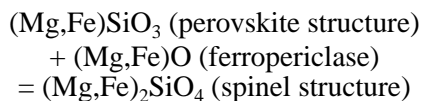
and, slightly later, another reaction transforming the remaining Mg-perovskite into majoritic garnet:

$$(Mg,Fe)SiO_3 \text{ (perovskite structure)}$$
$$= (Mg,Fe)SiO_3 \text{ (garnet structure)}.$$
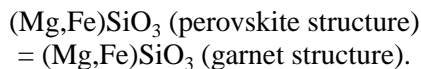
Therefore, at higher horizons, ringwoodite and majorite would precipitate in cotectic proportions, which, judging from the position of forsterite–majorite eutectic in the system MgO–SiO$_2$ [55], may be close to ca. 70% of majorite.

In a pressure range of 17–14 GPa, ringwoodite would be replaced in polybaric cotectic by wadsleyite (Mg–Fe orthosilicate with distorted spinel structure), and below ca. 14 GPa (depth of ca. 1150 km), wadsleyite gives way to olivine. Between 1150 and ca. 600 km, olivine is supposed to be less dense than the melt [29, 30], and this must have important consequences for the subsequent path of differentiation.

When one of the solid phases is less dense by comparison with the coexisting multicomponent melt, two different situations may occur that differ in the sign of the slopes of isopleths of the liquidus surface of the floating phase, which for the solid phase of component i is governed by the following variant of the Clapeyron equation:

$$\left(\frac{dT}{dP}\right)_{\text{Liquidus}} = \frac{\Delta S_i^{\text{fus}} - R \ln X_{i(L)} + S_{i(L)}^E}{\Delta V_i^{\text{fus}} + V_{i(L)}^M},$$

where T and P are temperature and pressure, R is the universal gas constant, $X_{i(L)}$ is the mole fraction of i in the melt, ΔS_i^{fus} and ΔV_i^{fus} are the molar entropy and volume effects of melting of crystals i, $S_{i(L)}^E$ is the partial molar excess entropy of i in the melt and $V_{i(L)}^M$ is the partial molar volume of mixing of i in the melt.

The first of the two cases may be illustrated using a binary system with a simple eutectic as an example. We may have a system in which for both components crystals are denser than pure melts (as is usually the case), but due to the very large difference between the densities (or molar volumes) of these components in the molten state, there would be a certain interval of compositions where mixed liquids would be denser by comparison with the lighter of the two solid phases. For this to have significance for the crystallization differentiation, the range of compositions with liquids that are denser than crystals should overlap with the liquidus of the respective solid phase, because only in this range, which would also include the eutectic, would the crystallizing phase float instead of sink to the bottom. In this case, both melting curves for pure components and liquidus isopleths would have positive Clapeyron slopes, and the crystallization of both phases would result in a decrease in the total volume of the system.

When the cotectic of two minerals with contrasting densities is reached, the less dense phase starts to ascend, and, because the P–T slope of adiabats for ultramafic silicate melts are usually significantly less than the slope of the liquidus (adiabats for komatiitic melt are significantly flattened at high pressures [59]), the rising crystals soon reach the region of supraliquidus conditions and are dissolved in the melt. Thus, the denser phase remains near the bottom forming cumulates, whereas the less dense phase will float, and later it will be dissolved in the melt. In this way, the residual melt would be gradually depleted in components of a denser phase and enriched in the components of a less
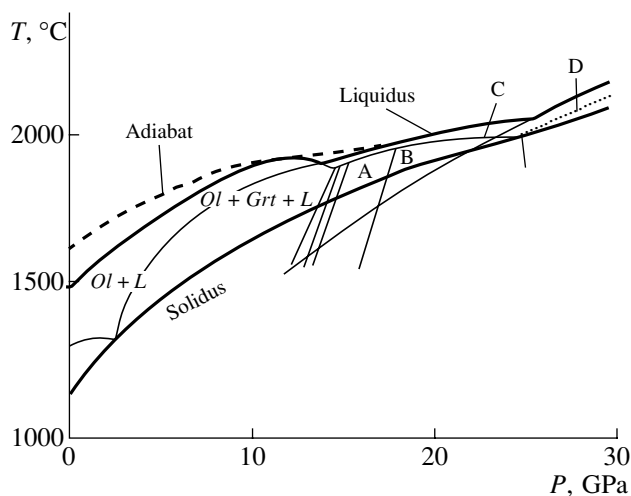
Fig. 4. *P–T* diagram for Allende carbonaceous chondrite [57] with adiabat for komatiitic melt ([59] – dashed line). *L*—melt, *Ol*—olivine, *Grt*—garnet, A—wadsleyite + garnet + melt, B—ringwoodite + garnet + melt, C—garnet + melt, D—ferropericlase + garnet + melt. Note that due to the maximum on the olivine liquidus the adiabat may touch the liquidus twice.

dense solid phase. The resorption of a less dense phase would stop when the liquidus front reaches the neutral buoyancy level, and after that, it would probably crystallize near this level alone forming suspended cumulate. The denser phase would accumulate near the current position of the bottom, and the residual melt trapped between the two cumulate layers would finally solidify forming rock with high concentrations of incompatible elements.

In the second case (the partial molar volume of the components of lighter phase in the melt is less than the molar volume of the solid phase), liquidus isopleths would have negative slopes in *P–T* coordinates, either because ΔV_i^{fus} is negative (i.e., for pure component *i,* the melt is denser than solid phase) or because $V_{i(L)}^M$ has relatively large negative value: i.e., the melt becomes significantly denser on mixing. If for a given phase, solid–liquid density inversion is observed, then there should be a maximum on the liquidus isopleths of component *i*, which is likely to be situated at a higher pressure in comparison with the position of the neutral buoyancy level. Crystallization of the less dense phase increases the total volume of the system in this case.

If the temperature maximum occurs on the liquidus of ultramafic composition, then, at some stage, the adiabat should intersect the liquidus at two levels: near the current bottom and at some higher level but lower than the zone of neutral buoyancy. At the higher level, the solid phase of lower density should crystallize alone, and it would ascend toward the level of neutral buoyancy. This would shift the composition of the underlying molten layer from the cotectic, and near the bottom

the denser of the two phases may crystallize alone. As in the first case, two layers of cumulates would be formed with the residual melt between them.

Which of these two cases was realized for the Martian magma ocean cannot be said with certainty at the present stage of our knowledge, because the liquidus for the composition of the Martian primitive mantle has not been studied experimentally. The liquidus of pure forsterite does not show the presence of a maximum [60], but the *P–T* slope of the liquidus decreases dramatically from ca. 78 K/GPa at 1 atm to 14 K/GPa near 14 GPa; so it is not excluded that in a multicomponent system change of the partial molar volumes of olivine components would result in the maximum on the liquidus of this phase. No maximum on the olivine liquidus has been found for the bulk composition of the terrestrial fertile lherzolite [52], but it was observed for the composition of Allende carbonaceous chondrite [57]. Comparison of this liquidus with the position of the adiabat for komatiite melt [59] shows that at a certain stage the adiabat may touch the liquidus at two levels (Fig. 4). The composition of the Martian primitive mantle is closer to the silicate melt of Allende than to terrestrial lherzolites: all three compositions have approximately chondritic proportions of major elements, but the Mg/(Mg + Fe) ratio is close to 0.9 for the Earth, 0.75 for Mars [12], and 0.7 for Allende silicate melt [57]. Therefore, it is not excluded that the temperature maximum existed on the olivine liquidus for the Martian magma ocean, and this would promote the formation of two separate nearly monomineralic cumulate layers, garnet near the bottom (ca. 1400 km) and a suspended olivine-rich layer near the level of neutral buoyancy (ca. 600 km).

The liquid layer below the suspended olivine cumulate pile would be separated from the rest of the magma ocean, and it will gradually solidify by precipitation of garnet and olivine, which would later be joined by clinopyroxene and possibly by some other minerals concentrating incompatible elements. The late stage residual melt will solidify beneath the olivine cumulate pile. It is not excluded that this differentiated residual melt would penetrate in some places into the overlying olivine-rich rocks causing their geochemical heterogeneity, i.e., creating in them zones enriched in highly incompatible elements.

The part of the magma ocean above the olivine-rich layer would gradually crystallize near the bottom during the subsequent cooling by coprecipitating olivine and garnet, which would later be joined by clinopyroxene; then, at some higher level, garnet would disappear from the near-liquidus phase assemblage, and orthopyroxene would appear at some later stage. The residual melt, which should consolidate in the uppermost part, will probably create a primordial crust enriched in incompatible elements.

The outlined scenario of the solidification of the Martian magma ocean is of course very hypothetical

due to the scarcity of experimental data on the subliqui-dus equilibria for the model compositions of the Martian primitive mantle and our very approximate knowledge about the parameters governing this process. One of the most important of these parameters is the initial depth of the magma ocean. Depending upon the available thermal energy, the Martian mantle might have been not completely molten but only to some intermediate depth. Such a scenario has been favored for the Earth and other planets in a number of publications [44, 45, 61]. If the Martian magma ocean were not mantle-wide but extended deeper than the olivine–melt density crossover, then, qualitatively, the final result would be the same as outlined above, but the lower part of the mantle would consist of undifferentiated primitive lherzolite, and the overlying products of magmatic crystallization would be less differentiated. In any case, the mid-mantle layer of olivine-rich rocks would be a suitable source for the generation of the primary magmas of SNC meteorites in terms of major components.

Although the major element composition of these estimated primary magmas is consistent with their common source and similar condition of partial melting, the trace element characteristics and isotope systematics reveal significant differences between different groups of SNCs. This may be explained by the varying degrees of crustal contamination [41, 42] or by the heterogeneity of the olivine-rich mid-mantle layer caused by the infiltration of residual melts soon after its formation, as was discussed above.

It has been noted that for a long time volcanism on Mars has been restricted to only two regions (predominantly, to Tharsis) of this planet. This fact has been explained by the modeling of the convective evolution of the Martian mantle, which shows that in a planet with endothermic phase transition occurring close to core–mantle boundary, a single-plume pattern of convection gradually develops due to suppression of all but one or two upwellings [62]. If the Martian mantle is compositionally layered and this stratification has been preserved from the time of the solidification of the global magma ocean, then an alternative explanation of the confinement of Martian magmatism to two regions becomes possible. It has been suggested above that the ascent of plumes from the olivine-rich cumulate layer might have been caused by heating from below due to radioactive decay in the products of crystallization of residual melt trapped between olivine-rich and garnet-rich cumulates. It is possible in this case that the incompatible element-rich material may not be distributed below the olivine-rich zone uniformly but rather formed giant batholiths confined to certain localities. In this case, the sources of heat would be localized in the same position within the Martian mantle, and magma generating plumes would be created only above these heat sources during the last period of Martian geological history.

CONCLUSIONS

(1) Primary magmas for all the investigated SNC meteorites have similar compositions in terms of major elements. These compositions are high in Mg + Fe and Si mole fractions, and they are similar in this respect to terrestrial boninites.

(2) These primary magma compositions could only have been produced by small degree partial melting of an olivine-rich source, which could be related to the Martian primitive mantle either by previous episodes of the extraction of basaltic melts, which formed a very thick crust, or by formation of olivine-rich cumulates during the consolidation of the primordial magma ocean, which originally had the composition of the Martian primitive mantle (similar to terrestrial pyrolite, but with a significantly higher Fe/Mg ratio [12]).

(3) The estimated contents of heat producing elements in this olivine-rich source are very low, and they are likely to be not sufficient to provide energy for magma genesis, if the whole of the Martian mantle now consists of such very depleted harzburgite.

(4) The hypothesis is favored that assumes primitive magma generation in the olivine-rich cumulate pile originally formed during the consolidation of the primordial global magma ocean.

(5) The existence of a maximum on the olivine liquidus of Martian primitive mantle composition, by analogy with the melt from Allende carbonaceous chondrite [57], is very probable, and it would facilitate separate crystallization of olivine and garnet with the formation of olivine cumulates from the garnet-depleted melt.

(6) The solidified layer of residual melt, which underlay the olivine-rich cumulate pile, may be enriched in incompatible elements, including K, U, and Th, whose radioactive decay might have provided heat for the generation of plumes in which primary magmas of SNC meteorites originated at higher levels.

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