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ON THE THERMODYNAMICS OF METEORITES AND PARENT BODIES III: BASALTIC ACHONDRITES IN AN INCREASING SIO_2 SEQUENCE AND COMPARISON OF THE ROLE OF DIOGENITES AND KOMATIITES IN PLANETARY EVOLUTION

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ABSTRACT

After chondritic thermal metamorphism the thermal evolution of a primitive achondritic mineral assemblage continued by partial melting and outflow of the metal-sulfide components and of the low melting point basaltic components. Metal-sulfide assemblage migrated toward the center, basalt migrated toward the surface of the asteroidal parent body. In our paper the HED basaltic achondrites are arranged into a sequence by their increasing SiO_2 content: diogenites, howardites and eucrites. Comparing this sequence with that of terrestrial basalts of komatiites, picrites and tholeiitic basalts we found a similar bulk thermal evolution trend for them. We give an overview about both of these sequences as a long term planetary evolutionary differentiation sequences by inserting them into the thermal evolution of a solid body. General main trends in planetary differentiation are also discussed.

INTRODUCTION

During the last seven years our Cosmic Materials Space Research Group had excellent opportunities to study and compare different basalts and related rocks from the Solar System (BÉRCZI et al, 1997). Over the rich set of terrestrial basalts and andesites from both Hungary and from elsewhere on the Earth we had lunar basalts from the NASA Lunar Sample Thin Section Set, (12002, 12005, 70017 basaltic and 74220 picritic samples, MEYER, 1987), achondritic HED basalts from the NIPR Antarctic Meteorite Thin Section Set, (Y-74097 and ALHA-77256 diogenites A and B, Y-7308 howardite and Y-791195 and Y-74450 eucrites A and B, YANAI, KOJIMA, HARAMURA, 1995), Martian basalt samples from both NIPR and NASA Antarctic Meteorite Thin Section Sets: ALHA-77005 (NIPR), EETA-79001 (NASA). Over these samples of four planetary bodies (Earth, Moon, Mars, and Asteroid - probably Vesta) we know compositional data from the Venera and Vega Venus lander spacecraft (KARGEL, KOMATSU, 1992) and temperature measurements of Galileo in the vicinity of Io (KESZTHELYI et al, 1998, MATSON et al, 1998, WILLIAMS et al, 2000) which also refer important early Solar System type volcanic rocks. In our statistical comparisons all these planetary bodies and data sources were considered and studied.

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Basalts play the role of the "common denominator" among rocky planetary bodies of terrestrial type because partial melting of various chondritic precursor materials give basaltic partial melts. Over their common basaltic nature all these melts preserved stamps of the thermal history of their source parent body, too. In general: our expectation is that if the body was small, thermal history was short and the time scale for basaltic volcanic events resulted in not so various differentiated melts. At the same time stamps by small gravity could be deciphered in the crystallization history of basaltic achondrites of an asteroidal sized body. But contrary to the scale differences between parent bodies common trends in the sequence of basalt compositions were revealed when the whole range of thermal history span of the basaltic volcanism of different sized bodies had been studied (LUKÁCS, BÉRCZI, 1997, 1998).

In this work we focus on the common characteristics of the evolution of basaltic partial melts on a solid rocky body. Gravitational separation less affects the smaller body then the larger, but during the crossing of basaltic melts across thicker and thicker crust layers on any body characteristic changes for this basaltic melt composition will be similar: for example on both large and small bodies they would become more and more Ca-Al rich in the later and later eruptions (from deeper and deeper sources).

In our paper we compare the similarities and differences of basaltic magmatisms on rocky planetary bodies. We consider two main trends basically: the terrestrial evolution and an asteroidal evolution. Other planetary bodies will be interpolated between the two wedges, and will be considered as various branchings from or levels of the common evolutionary trend. Because the terrestrial compositional separation in the atmosphere had got a name after the barometric height formula, we give such name to the compositional separation in the solid part of the rocky planetary bodies. Therefore we call it barometric basaltogenesis on rocky planetary bodies when we study planetary differentiation.

RECAPITULATION: EARLY THERMAL EVOLUTION OF CHONDRITIC PARENT BODY

Before studying the basaltic period of the chondritic body evolution we summarize some key events from the earlier two periods. Starting from parent bodies with different initial composition (E, H, L, LL, C) we formulated evolutionary paths of these parent bodies in the Fe+FeS vs. Fe-oxides compositional field. In this earlier statistical investigations (BÉRCZI, LUKÁCS, 1995, BÉRCZI et al, 1996, LUKÁCS et al, 1997) we calculated the main paths of thermal evolution for chondritic parent bodies of E, H, L, LL, C projected to the UREY-CRAIG (1953) Fe-compound field and VAN SCHMUS-WOOD (1967) table. This part of the thermal history of chondritic parent bodies began with thermal metamorphism, some diffusion processes and slow transformations of the chondritic texture, and advanced forward iron accumulation and outflow to form a core. In the evolutionary path projections in the UREY-CRAIG (1953) field (given by the Van Schmus-Wood type-numbers of metamorphism, as a degree of diffusion) the compositional sequences showed *first reduction then oxidation* transformations (E, H, L, LL, C chondrites). Reduction and C loss, between 3-4 petrologic types, was also recognized earlier (LUX et al, 1980, HUSS et al, 1981, SCOTT et al, 1984), the oscillation between oxidized and less-oxides states, which occurred between the 4-5-6 middle petrologic types, this was our groups's recognition (BÉRCZI et al, 1998, LUKÁCS et al, 1998).

After thermal metamorphism further heating results in segregations in the chondritic asteroidal body. Partial meltings begin and the primitive achondritic assemblage segregates two types of materials. First is the metallic/sulfide melt which migrates toward the depths to form a core (or to collect into great blocks). Second is the melt of lower melting point silicates, which form basaltic melts which migrate toward the surface. We studied these two stages of the chondritic body evolution in our last year paper (BÉRCZI et al, 1999). There we extended the chondritic thermal metamorphic transformation sequence till the basaltic achondrites. The gradual transition from chondritic mineral assemblages (and compositions) through different primitive achondritic stages to the most differentiated basaltic achondritic meteorites was divided into two main stages. Stage A was the earlier partial melting and outflow of iron-sulfide stage (acapulco, lodranite, winonaite), stage B was the later partial melting of a low melting point basaltic like component and its outflow toward the surface (leaving ureilites and some lodranites in their less primitive achondritic state). This division of the chondrite to primitive achondrite range made it possible to distinguish different types of primitive achondrites (BÉRCZI ET AL, 1999). The flow-chart of the chondritic body evolutionary stages is given on *Fig. 1*. Now we study the segregated basaltic achondritic rocks, originating from the surface or near surface layers of an evolved asteroidal body, probably Vesta.

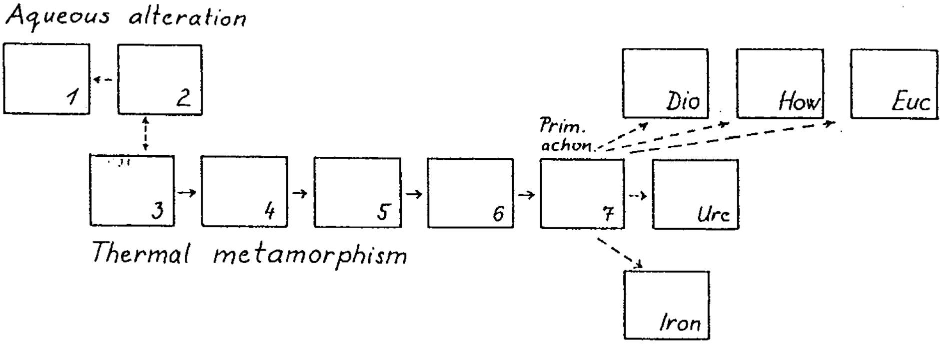


Fig. 1. Summarizing flow chart about the main blocks of thermal evolution of a chondritic parent body. The process starts on left with thermal metamorphism where milestones are the van Schmus-Wood types from 3 to 6, then primitive achondritic stage A and Stage B follows, finally separation of the partial melts in the form of a metallic iron+sulfide component, and a basaltic component follows. Our paper deals with the last period observable on the surface of an evolved parent body: the diogenite-howardite-eucrite sequence.

DIOGENITES, HOWARDITES, EUCRITES

Among meteorites the basaltic achondrites compose a complex series of mafic and ultramafic rocks. They represent a crust rock series with magmatic origin but frequently suffered brecciation on or near the surface of a larger asteroidal body. (According to the **H**owardite, **E**ucrite and **D**iogenite names they are shortly mentioned as HED meteorites.) Essentially the diogenite-howardite-eucrite series consists of rocks mineralogically composed of pyroxenes and feldspar. In the case of the diogenitic endmember the dominant pyroxene is Mg-rich orthopyroxene, the texture is a recrystallized granular. The other endmember in the series is the cumulate eucrite with pigeonite+plagioclase mineral components.

Along the diogenite-howardite-eucrite (DHE) series we find non-brecciated and brecciated types of textures with monomict and polymict breccias of the later. After a decade of classification debate about the detailed distinction between the groups finally the weight of the diogenitic component (orthopyroxene) became the distinctive component in separating the groups.. Howardites are transitional between the diogenitic and eucritic endmembers of the series (DELANEY et al, 1983). The howardite/eucrite separating line is at the 10 weight percent diogenitic (magnesian-orthopyroxene) component in the polymict basaltic achondrites. Above this value the polymict basaltic achondrites are howardites, below this line the basaltic achondrites are polymict eucrites (DELANEY et al, 1983).

New discoveries of basaltic achondrites in Antarctica triggered a new period of studies of basaltic achondrites (i.e. MITTLEFEHLDT, LINDSTROM, 1992). Granular orthopyroxenitic diogenites were classified to a Diogenite A group. Brecciated pigeonite-plagioclase diogenites were classified to Diogenite B group (TAKEDA, MORI, 1985). Today that is the accepted boundary between the two endmembers and the howardites in between that if a brecciated diogenite or eucrite contains less then 10 percent foreign breccia (so it contains more then 90 % of its original diogenitic or eucritic mineral assemblage) then its category would be polymict diogenite or polymict eucrite, otherwise all polymict basaltic achondritic breccias are howardites.

As a summary, according to the textural characteristics the DHE sequence contains 5 representatives. Along the series, starting from Diogenite A (monomineralic opx crystalline texture) from Diogenite B, (brecciated, mostly monomineralic opx texture) the participation of the pigeonitic monocline-pyroxene in the mineral composition increases, while the hypersthene component decreases, and the Fe-content of the pigeonite also increases through howardites (brecciated opx+cpx+plagioclase texture) toward the eucrites (brecciated eucrite B), till the microgabbro textured Eucrite A endmember. So considering the textural sequence a more detailed Diogenite A, Diogenite B, Howardite, Eucrite B and Eucrite A series is the object of our studies. But because we study mainly the chemical compositional data, mostly we restrict our formulations for the DHE series

The continuous sequence of these brecciated rocks of basaltic achondrites allows magmatic deduction and comparison only for endmembers. Diogenitic orthopyroxenites of pigeonite+plagioclase basaltic eucrites can be the representatives of the basaltic volcanism of an evolved asteroidal body. Diogenites represent those magmatic ultramafic rocks which were segregated from a chondritic precursor asteroidal mantle and migrated to the near surface region. Even if they were exposed as an early volcanic rocks, they were later overlapped by the younger eucritic basalts. In a thermal model of the following sections we shall show that earlier large scale (larger degree) partial melts (diogenites) might have been followed by the lower degree partial melts (eucrites) as we find it in the terrestrial case. The fact that at least two different magmatic rocks can be found in an asteroidal sized body shows that thermal evolutionary process may have advanced in a smaller rocky type body in the Solar System. Even if impact mixing produced the intermediate howardites, the gradually decreasing Mg-content of the diogenite-howardite-eucrite sequence is a valid characteristic of basaltic achondrites.

KOMATIITES AND RELATED ANCIENT ROCKS FROM EARTH

After recapitulation of the early evolutionary steps in chondritic asteroidal body evolution and overview of the basaltic achondrites we give a short summary about the komatiites and related ancient volcanic rocks on Earth, too. Our hypothesis is that from differentiation historical aspects komatiites from the Earth are far counterparts to the diogenitic type basaltic achondritic volcanism on an asteroid.

Komatiites are ultramafic Archean rocks with high MgO content (VILJOEN, VILJOEN, 1969, NESBITT, SUN, 1976, GLIKSON, 1993,). They were first identified and described in South Africa from the valley of the Komati river (VILJOEN, VILJOEN, 1969). The original Barberton komatiite had, according to the early definition: composition with MgO>9 %, K_2O<0.9 %, TiO_2<0.9% and CaO/Al_2O_3>1. (Spinifex texture is characteristic for Archean komatiites, but it is almost never seen in Phanerozoic rocks of similar chemistry.) Later, the Ca/Al criterion (NESBITT & SUN, 1976) extended the circle of komatiites, and they were identified in Australia, (Pilbara, Yilgarn, i.e. EWERS, HUDSON, 1972), in Canada (Abitibi, Munro Township, ARNDT, NALDRETT, PYKE, 1977), in Siberia, (Norilsk, i.e. NALDRETT, 1997) in the Eastern European Platform (Voronyezs, i.e. KRISTIN, 1980) and many other places. They were found mostly in Archean cratons as ancient multiple layers of thin lava flows, (characteristic to the lunar mare volcanism, too). Dividing the wide MgO range into peridotitic and basaltic komatiites it was shown that on the (Mg,Ca,Al) triangle the komatiites are adjacent to picrites and tholeiites (CONDIE, 1981) and their relations to the picrites (the komatiite-picrite-tholeiite sequence) was also investigated (i.e. JACOB ET AL, 1994, KEAYS, 1995, ANDERSON, 1995). Archean tholeiites are not so Mg-rich as compared to komatiites (Al>Mg), but they would be Mg-rich among modern basalts.

Space probes discovered that komatiites also occur on other planetary bodies of the Solar System. Over the lunar counterparts the interplanetary role of komatiites were strengthened by their probable occurrence on Venus, Mars and Io, on the basis of different measurements. On the Jupiter's Galilean satellite Io the surface temperature was extremely high (KESZTHELYI ET AL, 1998, MATSON ET AL, 1998, WILLIAMS ET AL, 1998, 1999, 2000), on Mars the lava tube and bedrock erosion was suggested by komatiites (BAIRD, CLARK, 1984, WILLIAMS, LESHER, 1996), and also the nakhlite-shergottite petrologic relations to komatiites of martian meteorites were suggested (TREIMAN ET AL, 1996, RUZICKA ET AL, 1998). On Venus the compositional characteristics on two landing sites (Venera 14 and Vega 2 measurements) made it probable that komatiites occur (i.e. KARGEL, KOMATSU, 1992).

PARALLEL RUN OF THE D-H-E AND THE K-P-T SEQUENCES ON THE MgO PLOT

New interplanetary importance of komatiites and related rocks emerged in our petrologic comparison studies carried out on bulk compositions of meteorites and differentiated planetary rocks from the Solar System (LUKÁCS, BÉRCZI, 1997, 1998). We observed on the Mg/Si vs. Fe/Si plots that different komatiitic rocks (from lherzolitic komatiites to komatiites) cover a wide range of MgO composition. The higher MgO range beginning from lherzolites, continues with komatiites and over picrites to the lower MgO containing tholeiitic basalts, too. On the basis of meteorite statistical investigations we observed that this komatiite-picrite-tholeiite sequence (KPT) has a counterpart among the basaltic meteorites (which are very probably the fragments of asteroid Vesta). This diogenite-howardite-eucrite (DHE) basaltic achondrite sequence covers the similar MgO range in the Mg/Si plot from higher (diogenite) to the lower (eucrite) MgO containing ones. These two very parallel Mg-rich to Mg-poor ranges (of basaltic achondrites and komatiite, picrite, tholeiite sequence) were separated by a gap, which was caused by the great difference in their Fe/Si content (LUKÁCS, BÉRCZI, 1997, 1998). Our explanation was about the gap that the Fe/Si content was sensitive to the gravitational separation of chemical components on the planetary body. The stronger gravity field and long time activity of Earth's magmatic processes "extracted" more iron from the crust and near crust rocks, separated and arranged gravitationally the Fe content of mantle rocks more effectively, then it could have been done by a smaller body. These preliminary results initiated this work. (*Fig. 2.*)

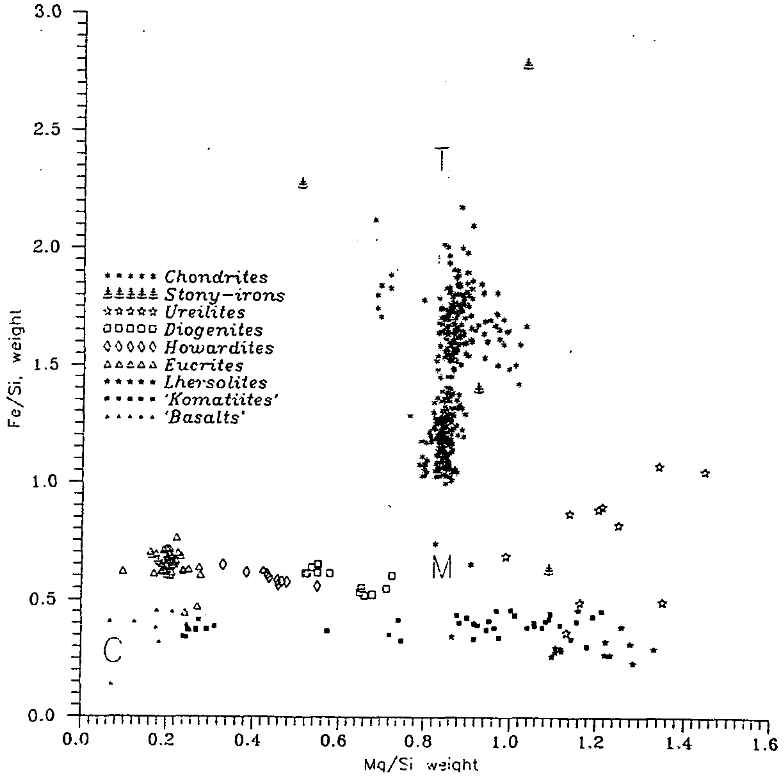


Fig. 2. Si normalized compositional field where chondritic, achondritic and some terrestrial compositions were compared. The Fe/Si vs. Mg/Si plot shows the decreasing Mg content of erupted basaltic magma production both on large and on small rocky body. The chondritic cloud of data (initial condition) can be found at higher total Fe contents because they were not separated yet by iron core forming first differentiation. Iron core formation takes the first distinction between bodies by the mass of the bodies: The higher Fe content of achondritic sequence shows that the separation of Fe compounds on a smaller body could have not been so effective as on a larger body (Earth). The composition of basaltic lava from mantle changes by the thickening of the crust. Crossing thicker crust resulted in lava gradually poorer in Mg as time advanced. Earlier high Mg containing komatiites were followed by later picrites and finally recent low-Mg lava on the Earth. Similarly, we may infer such a sequence of events on a differentiated asteroidal body (Vesta) too. First diogenitic, later howarditic and finally eucritic lava was there erupted onto the surface

We now formulate our conjecture. Since on Earth komatiites rather belong to the geologic past, the analogous diogenites may have been the first lava on Vesta, and when the crust was already substantial, the more aluminous eucrites followed, just before all the Vestan volcanism stopped. These lavas became eucrites, because they contained much Al and Ca (even if assimilated them from the thick crust which they crossed slowly or if they were small degree of partial melting of the asteroidal mantle).

In the following section first we sketch thermal history of Earth by giving parallel cross sectional overview of its main elementary components. Then we do the same for an asteroidal body during its evolution. Then we carry out statistical analysis and comparison of terrestrial and meteoritic data to see the main similarities and differences between the two magmatic rock series, one on the Earth and one on an asteroidal sized body. In this section we project the Si normalized main element bulk compositional data on different compositional fields which characterize evolutionary processes on planetary bodies. (Chondrites and achondrites data were taken from YANAI, KOJIMA, HARAMURA, 1995, those of Earth main rock types from CONDIE, 1981, and NIXON, 1989.) Parallel with our basaltic rock comparisons we sketch a partial thermal evolutionary model for the Earth, too. This emphasizes the role of crust thickening and compositional changes of partial melts in the thermal evolutionary history of Earth.

CROSS SECTION OF THE LAYERED EARTH AND A SIMPLIFIED MODEL OF ITS FORMATION PROCESS DURING THE TERRESTRIAL THERMAL EVOLUTION

We know that some part of Earth's interior is partly molten, and this partially molten material is the source of volcanism. We know that Earth's matter is vertically arranged into zones, mainly via gravitational separation, so around the center there is a dense core (we guess that it is iron), while going outwards the density decreases, mainly with Mg-silicates in the mantle and with mainly Al- and Ca-silicates in the crust. The reason of density zones: Fe's mass density is 7.8 g/cm^3, for the average Mg-silicate this is cca. 3.3 g/cm^3, while for Al-silicates cca. 2.8 g/cm^3. (In these points geophysics and geology treat the questions in more details, but for our present purposes we do not need those details.)

In the upper crust (having much Al-silicates), Al is much more abundant than Mg. At the same time, in the meteorites generally the Al/Mg ratio is opposite, because in the cosmic abundance Mg is one order of magnitude more abundant than Al (NOVOTNY, 1973), and this is also expected from nuclear physics. Namely, in the cosmic nucleosynthesis both Mg and Al (and also Si) form by fusion from the (CNO) triad. Now, Mg is an even-even nucleus and Al is not, so Mg is preferred in the concurrent processes. Therefore we have one more argument that some process enhanced Al content of the crust. It can be conjectured that the enhancement was the result of two selection mechanisms.

The first selecting mechanism is gravity. After accretion the material assemblage forms a sphere, partial melting begins in its interior, and if there is enough time, hydrostatic equilibrium will be achieved with the appropriate gradients of composition. Without convection the change of compositions with radius would be a generalization of the barometric formula known from terrestrial atmosphere (BALÁZS, 1971); if convection is present, then the gradients are smaller.

First we show an ideal layered body arranged according to these density relations. Consider a sufficiently large body with a molten chondritic composition. This body contain some 5-20 % of metallic Fe-Ni and FeS component. This assemblage is expected to flow out, being denser then silicates (and existing separated from the crystalline lattice of silicates). After flowing out it migrates to greater depths and accumulates around the center to form a core. (This molten metallic and sulfide Fe will contain also some C in solution, too) The overwhelming majority of the remaining material is a mixture of silicates, mainly of Fe-, Mg-, Al- and Ca-silicates.

The second selecting mechanism is melting. Silicates have various densities, and although densities depend on many details, roughly Fe- and Mg-silicates are denser and Al- and Ca-silicates are lighter. Then, in the molten sphere just above the iron core one expects a transition zone where iron is mixed with silicates (pallasites are the meteoritic representatives of this stage) while slightly more above silicates are mixed with iron. Emerging from the iron core along a radius we can observe that upwards the matter is a mixture of silicates, with continuously decreasing Fe and Mg content and with increasing Al and Ca ones. Finally we find the Al-silicate rich outer layers of the crust.

Now, let us repeat our simplified model which shows the great periods how this spherical body evolved while it was cooling. After some time a solid crust appeared, but below this early crust convection was still going on and it broke up crust time to time by volcanism. First probably the molten matter erupted along fissures, later it was possible mainly in spots. (On Earth even now both mechanisms go and mid-ocean ridge basalts do differ from hot spot ones). Anything were the details, the matter of lower density and/or melting point had higher chance to come up. Both density and lower melting point criteria prefer Al- and Ca-silicates; therefore during volcanism the upper crust became more and more enriched in these components. This was an oversimplified sequence of events but first these are the most remarkable steps that came from the principles of thermodynamics of open systems. Obviously, as the molten body cooled the molten zone have got deeper and its temperature also decreased. The crust became wider and wider, and this wider zone must had been crossed by the molten material. These changes have two consequences:

1) The rate of volcanism is decreasing in time (as it is in accord with geologic observations); and

2) The ascension of lava is taking more and more time (crossing thicker and thicker layers).

However, from the second point it follows that the ascending silicate becomes more and more like the crust silicates, which means that the silicates of high melting points "freeze out" from the ascending lava and this indeed leads to Al- and Ca-enrichment.

One can directly see today that the erupting material is not of the mantle composition. Estimated Archean mantle compositions were compared to old lherzolite inclusions, and they resembled each other, and the Al/Mg ratio was 0.1 (CONDIE, 1981). In present volcanism it is well above 1. Also, for the (Archean) mantle Na/Mg$\approx$0.01, while in the present volcanism it is $\geq$1. (The cosmic and terrestrial crust abundance, normalized by weight to Si, are shown on (*Fig. 3.*) until Z=30; the most important elements in the present argumentation are Z=11, 12 and 13, i.e. Na, Mg and Al, respectively. Although it is hard to directly verify, it is obvious that in times when the solid crust was thinner and ascending fluxes higher, the selection for Al and Na (light and of low melting point) must have been more moderate. So as much as Earth is evolving, so much the inner compositional gradients become higher and higher, and the uppermost surface goes farther and farther from the cosmic abundance (and also from the original composition).

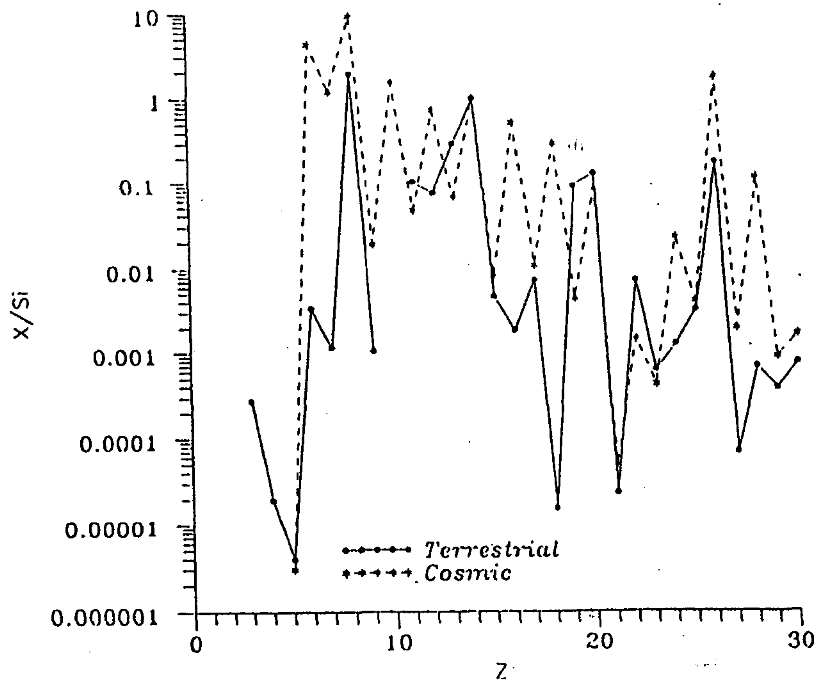
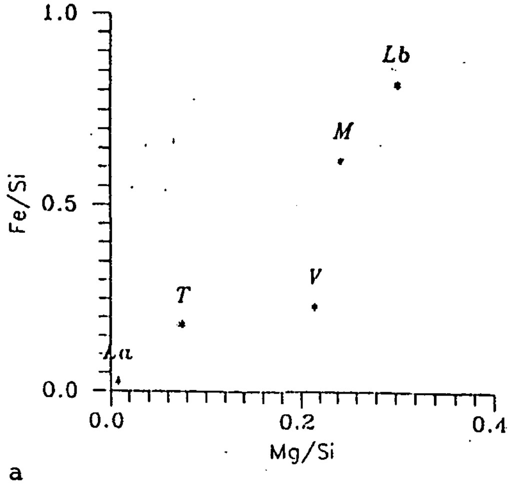


Fig. 3. Cosmic abundance of the first 30 chemical elements compared to the terrestrial abundance in the upper crust.

TERRESTRIAL-TYPE PLANETARY BODIES HAVE SIMILAR THERMAL HISTORY

From planetary surface compositional (and especially from known planetary basaltic) data it can be seen that the general cross section and the bulk thermal history happened similarly on another planetary bodies of the Solar System. Apollo expeditions collected great number of lunar samples, the Venera and Vega probes on Venus, and the Viking and Pathfinder probes on Mars measured surface compositions. All these compositions resemble better the terrestrial one than the cosmic abundance, as a result of planetary differentiation. The Martian sequence was compared to that of Terrestrial one by WANKE ET AL, (1997). They found that Martian rock samples, both SNC meteorites and Pathfinder rocks and terrestrial samples fall to two, almost parallel ranges, both in an MgO decreasing sequence. There the terrestrial komatiites had Martian counterparts in the ALHA-77005 and other high Mg/Si ratio samples (i.e. Chassigny, LEW-88516 and ALHA-84001, for nakhlites see TREIMAN ET AL, 1996), while recent ocean floor basalts had counterparts in Shergotty, Zagami and EETA-79001B samples (WANKE ET AL, 1997). On this Al/Si vs. Mg/Si plot it is clearly shown that Martian samples has lower Al/Si content than that of the terrestrial samples. (This fact may have early Solar System evolution causes, too.)



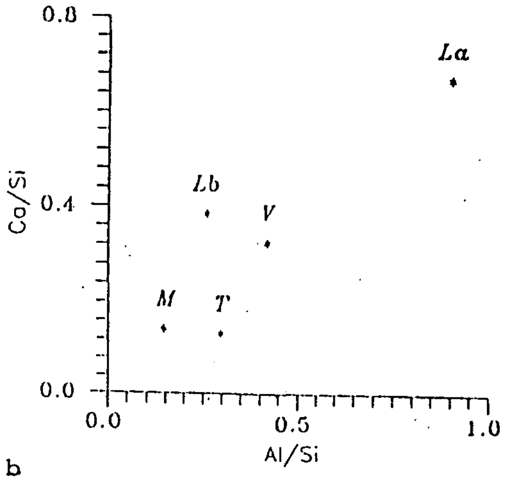


Fig. 4. Two maps for planetary surface rocks. 4a.) The Mg/Si vs. Fe/Si plot, 4B.) The Al/Si vs. Ca/Si plot, where T, V, M, La and Lb marks Earth, Venus, Mars, Lunar anorthosites and Lunar average, respectively.

Among Apollo lunar samples both 12002 and 74220 has picritic Mg/Si ratios (MEYER, 1987). Venera 14 and Vega 2 data, as was mentioned earlier, also refer probably komatiitic composition on Venus surface (KARGEL, KOMATSU, 1992). As for quantitative data, see *Fig. 4a.* where V stands for Venera 14 data, T is the average Terrestrial crust, M stands for the average of the two Martian Viking lander data, La is the Lunar Apollo 16 anorthosite, and Lb is the average of Apollo 11, 15 and 17 basalts (ENCRENAZ ET AL, 1989 RÖMPP, 1958; CIMBAL'NIKOVA ET AL., 1975, other Martian data in WANKE ET AL, 1997). We may observe on Fig. 4a. (planetary crust Fe/Si vs. Mg/Si plot, ignoring now the completely feldspathic anorthosite) that the Fe content of the surface rocks goes oppositely with the radius or mass of the planet. We guess that the main reason is the more and more successful gravitational separation of iron on these bodies.

The Fig. 4b. Ca/Si vs. Al/Si plot for planetary bodies shows that estimeting from the existing crust data local volcanism distingiushed the 4 planets: it has brought up substantial amounts of Al and Ca to the surfaces. Earth has a fully developed plate tectonics with several types of volcanisms. Mars had no plate tectonics and had shield volcanoes. Venus has volcanism, does not seem to have plate tectonics but some strange crust behavior instead. Finally Moon was too small for any plate tectonics (ILLÉS-ALMÁR, 1994). Still, all above planetary surfaces are far from the cosmic abundance and this cannot be simply the result of static gravitational separation only, because their Ca/Al ratios differ too.

CROSS SECTION OF AN ASTEROID AND THE ASTEROIDAL THERMAL HISTORY

Not only the rocky (terrestrial type) planetary bodies but the larger asteroids are spherical. Therefore they must have had a molten (most probably a partially molten) stage in the past, although their thermal fluxes were small fractions of Earth's one. The probable explanation is the primordial Al^{26} and Pu^{244}, relatively short-living radioisotopes. Ignoring other details for our present purposes, it counts only that the primordial molten stage had probably a chondritic composition. Then gravity can work and forms a minimal energy state sphere, and segragation+migration can rearrange the matter into zones. But in an asteroid, with $R \approx 500$ km at most, silicates cannot separate too successfully from each other. Still its gravity may be enough to collect molten metallic Fe and FeS The observational evidence is the existence of iron asteroids (the first on the list is Psyche 16), and their explanation is an originally zoned asteroid which later has lost the silicate outer layers in collisions.

Applying then the above theoretical scheme for the thermal history of a larger asteroid one can visualize a (hypotethical) totally molten initial stage: first an iron core and around it a more or less homogeneous, zoned onion-shell of the silicates appears. In the outer silicate shell - by cooling the outer parts - a frozen crust appears, and later it gradually grows. As the solid crust becomes substantial, again and again silicates of low melting point (and low density) have better chance to penetrate it. (Now the Fe content of the surface rocks could not decrease on asteroids with larger radius because of its small gravity as compared to the terrestrial planets.) Local volcanism can bring up considerable amounts of Al and Ca containing partial melts and this is shown on the Al/Si and Ca/Si plots, where both of these two components changes proportionally with each other. In the early volcanism the Al/Mg ratio of the asteroidal basalts (diogenites, howardites and eucrites) followed the global picture sketched for the larger bodies (*Fig. 5.*). (Basaltic achondrites, similarly to Mars, also have lower Mg+Al range than that of the Earth.)

Although this is an idealized and simplified theoretical scenario, the basic steps in layer separations could be shown on this model. In a real, chondritic asteroidal system, during the thermal evolution from chondritic to achondritic stage there are no signs of the totally molten state. In primitive achondritic (acapulcoite-lodranite) mineral assemblages only partial melting of different (low) degree and slow migration of partially molten phases could be observed (i.e. MCCOY ET AL, 1997). In larger asteroids this migration was more effective and resulted in separation of great iron core as the observational evidence of asteroids with metallic spectra have proved, (GAFFEY, BELL, CRUIKSHANK, 1989) and basaltic crust as basaltic achondrites witness it.

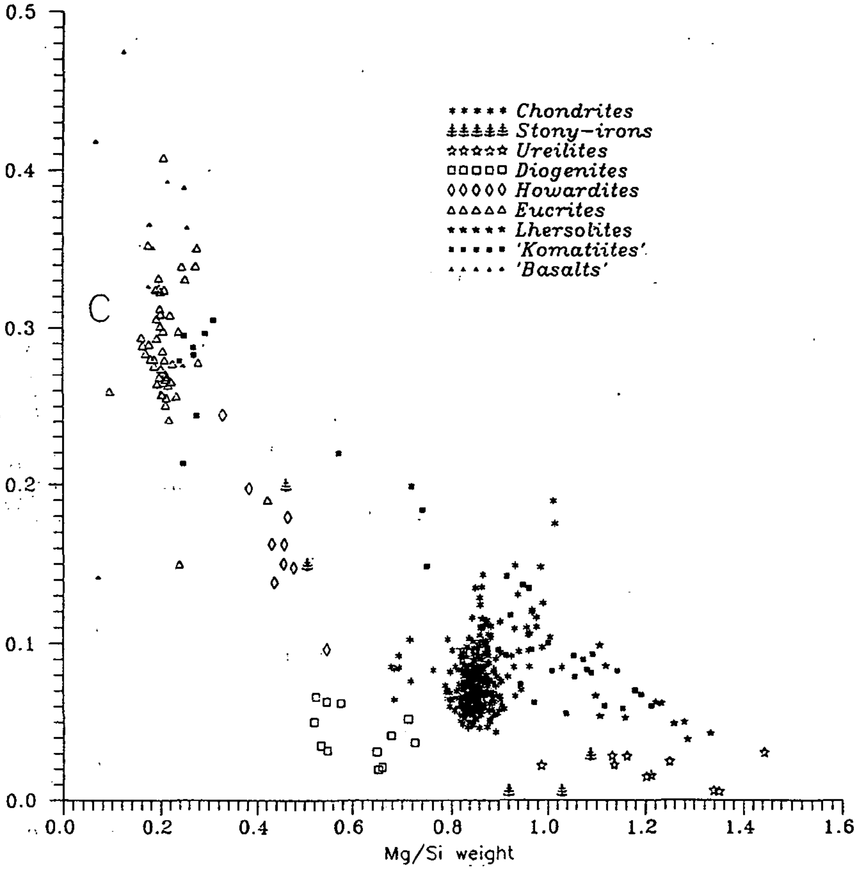


Fig. 5. The Al/Si vs. Mg/Si plot for basaltic achondrites and main terrestrial rocks studied in our work. It shows the main relation between Al and Mg during the long range basaltic evolution. They are essentially in anticorrelation, because differentiation of mantle results in separation of Al containing phases.

EVOLUTIONARY SEQUENCE OF THE TERRESTRIAL ULTRAMAFIC-MAFIC VOLCANISM KOMATIITES-PICRITES-BASALTS AND COMPARISON TO THE DHE SEQUENCE

Evolutionary models of the early Earth adapted the recognition of lunar magma ocean (ANDERSON, 1981). The terrestrial magma ocean model considered that significant fraction of the Earth's mantle was molten. After cooling a thin crust formed and this high degree of partial melting (with chondritic bulk composition) appeared as a buried magma ocean, (WALKER, 1983), which produced intensive eruptions of Archean komatiitic flows. Therefore komatiites were the surface expressions of the buried magma ocean (NISBET, WALKER, 1982). Our komatiite-picrite-tholeiite sequence fits and continues this model. The cooling Earth later had thicker crust, lower degree of partial melting in its mantle, the partially molten zone withdrawn to greater and greater depths while producing picrites after komatiites, and the recent tholeiites after picritic "middle-period" basalts (LUKÁCS, BÉRCZI, 1997). Our time sequence model also fits to the model of TAKAHASHI, SCARFE (1985) and others (i.e. HERZBERG ET AL, 1988) which explains the origin and rarity of Phanerozoic komatiites. Their model shows that the present Earth's komatiites could come up as partial melts of the mantle peridotite from depths of cca. 175 km, picrites from cca. 100 km, and tholeiitic basalts from 40-50 km. The depth of the source needs great migration time to reach the surface and long transportation time implies great compositional changes. In this respect our model is a 3 parameters system in which depth, transportation time, and transportational compositional changes parameters are involved.

Now we sketch the time sequence of terrestrial basaltic rock starting from the cosmic abundance. Comparing main rock compositions to that of cosmic abundance (Fig. 3.) we can clearly see how far that composition moved from the (hypotethical but very probable) initial composition. (The terrestrial compositional starting point may be the original Barberton komatiite given earlier (CONDIE, 1981). This initial composition at least for silicates was probably very near to that of a chondritic one. (Actually the undepleted terrestrial mantle is that kind of source which could preserved many bulk characteristics of the chondritic primitive Earth, although it segregated iron-and sulfide core, and it also continuously produces crust.) If the most ancient "basalts" were komatiites, (high degree of partial melting of the ancient mantle) then they were rich in Mg (therefore poor in Al and Ca), poor in K (and Na), also poor in Ti, but arbitrary in Ca/Al. These characteristics of komatiitic bulk composition are conform with a less differentiated stage, nearer to the original composition of a mantle after gravitational separation of iron+sulfide to core and at the beginning of thermal separation in volcanism. *Comparing the compositional characteristics of the komatiites and recent tholeiitic basalts to the cosmic abundance we can observe that komatiites point away from the present crust abundance towards the cosmic abundance.* Recent basalts are even farther away from the cosmic abundance.

Let us sketch the basaltogenetic situation caa. 3.5 Ga ago, in order to show a qualitative way about the long term changes in basaltic composition. This will help us in a later comparison of komatiites and diogenites. In Archean times the planetary body is already after the gravitational separation of iron from mantle, but the internal heat production is high and the crust is thin. (Internal heat production then was cca. 3 times the present one, so the heat flux was also threefold and the thickness of the crust was cca. 1/3 of the present; LUKÁCS, 1993.) Large fluxes drive serious convection, so Mg-silicates are still not too much attracted into the depth by gravity. In addition, the crust might have been aluminous, but it was still thin, so the mantle material changed relatively little while crossing through the crust. Then in the average 3.5 Ga basalts we expect much Mg. The reasons are the following: i) the matter just below the crust is still closer to the "chondritic" composition; and ii) not too much Mg freezes out while crossing), alkalia are present cca. in cosmic abundance (what would enrich them in the basalt not stopped by the thin crust). We expect Ti cca. in cosmic abundance because of the same earlier arguments. And just this is seen in the komatiites.

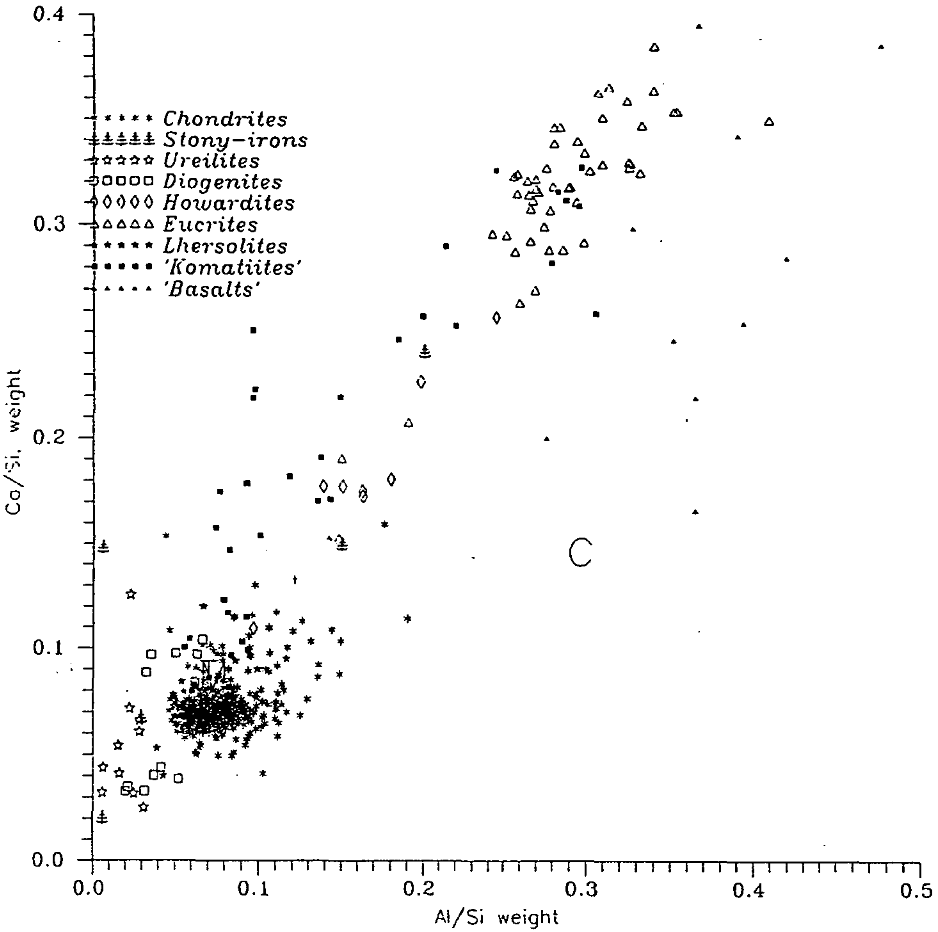


Fig. 6. The Ca/Si vs. Al/Si plot shows that these two elements are strongly correlated in most of the differentiation processes. On the most evolved Earth sometimes Al is more enriched when the outermost layers are considered. This shows that a larger body may reach more detailed, finer "barometric height formula" stratification of the main chemical elements - even if their holders are minerals - then the smaller asteroidal bodies.

Let us compare this evolutionary sequence to those data we know about HED basaltic achondrites (probably from Vesta). On the Fe/Si vs. Mg/Si plot (Fig. 2.) we show 5 types of materials: chondritic meteorites (NIPR data from YANAI ET AL., 1995), diogenite, howardite and eucrite (YANAI ET AL, 1995), and 61 terrestrial basalts of various kind (KRISTIN, 1980, CONDIE, 1981; NIXON, 1987; NEALE, TAYLOR, 1992). We can see that the sequence of the terrestrial ultramafic-mafic volcanic rocks are the most Fe-poor (roughly independently of the widely varying Mg content). Also the figure shows the approximate location of Earth's crust (C), mantle (M) and the whole planer (T). Observe here that:

1) the basaltic achondrite sequence form a line parallel to terrestrial basalts (but with higher Fe content);

2) the most Mg-rich asteroidal basaltic achondrites have the same Mg/Si as that of the chondrites;

3) the chondrites contain more Fe than either terrestrial or asteroidal basaltic-ultramafic rocks.

Fig. 6. shows the Ca/Si vs. Al/Si plots. Chondrites form a dense cluster (hiding among themselves T and M). Almost all the basalts (of any planetary body) fit to a straight line starting from the origo and crossing the chondritic cluster, and all points except for some normal terrestrial basalts lie on a proportionality line where the ratio is the cosmic abundance ratio. It seems that basaltogenesis substitutes indeed Mg with Al and Ca, but cannot prefer one of the latter to the other.

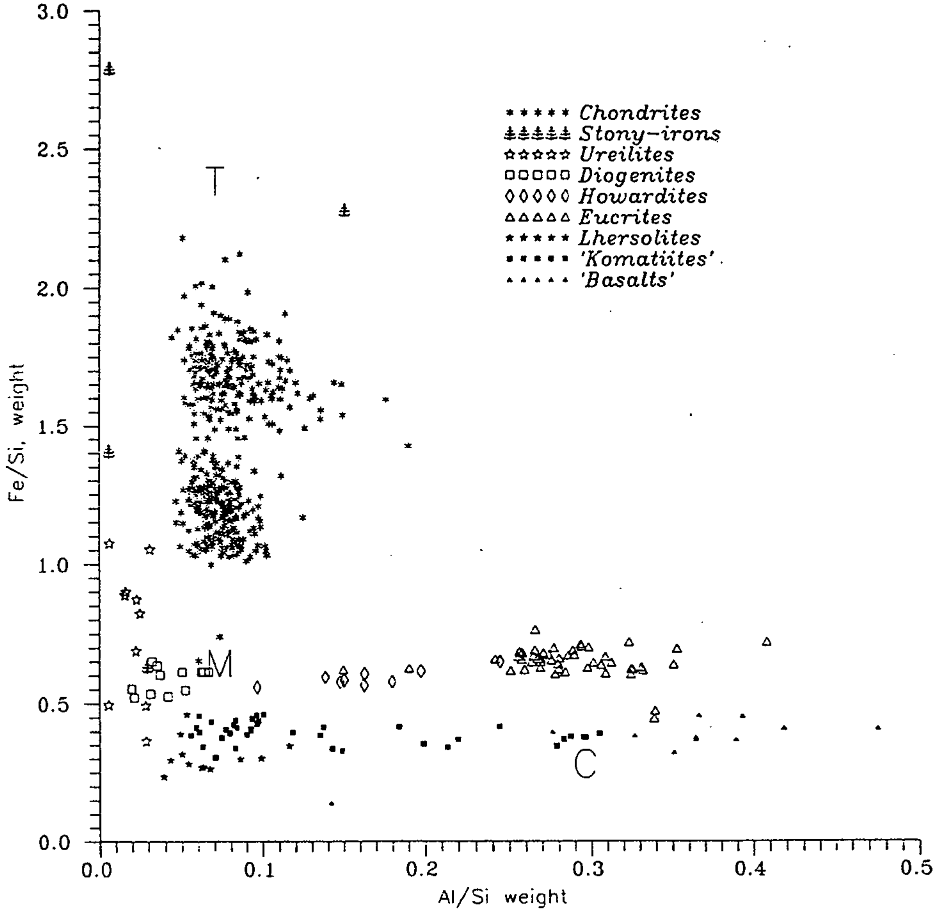


Fig. 7. The Fe/Si vs. Al/Si plot also shows that Fe distinguish different levels of differentiation from the ancient chondritic (highest level of bulk Fe/Si ratio) to the most differentiated terrestrial basalts (the lowest Fe/Si ratio). In the two evolved body dataset we can see to long range of differentiation sequences. One is for achondrites, (upper one) the other from the Earth (the lower one). Both sequences span a wide range of Mg content. The lower Al end basalts of the sequences are the earlier, the greater Al containing basalts are the younger basalts.

All the some element/Si vs. Fe/Si figures (i.e. Fig. 7.) suggest that in the primordial basaltogenetic processes the metallic Fe have been lost by gravitation. All the figures clearly show the analogy between diogenites and some komatiites. At the same time eucrites, (and also lunar basalts), are counterparts to "modern" terrestrial basalts. At this point we return to our original hypothesis, the role of the time sequence of the appearance of these rocks. Since on Earth komatiites rather belong to the geologic past, the analogous diogenites may have been the first lavas on Vesta. This is a profound conclusion of the parallel DHE and KPT sequences on the material maps shown. When the crust was already substantial, the more aluminous howardites might have followed and finally, just before volcanism stopped on Vesta, the lava became eucritic with even higher Al and Ca content. We have another argument in accordance of this hypothesis. We can see in datasets that the Ti content of basaltic meteorites is growing as volcanism becomes more difficult (BÉRCZI ET AL., 1997). The Ti/Si ratio is the smallest in chondrites (hardly above the cosmic abundance), it is growing in the diogenite -> howardite -> eucrite sequence, in lunar basaltic meteorites it is similar to eucrites (and terrestrial basalts), and the last stage is represented in later stage lunar blue basalts (BÉRCZI, LUKÁCS, 1996), not yet found as Antarctic meteorite. Now, remember that a komatiite criterion is the low abundance of Ti.

SUMMARY: MAIN TRENDS IN FRACTIONATION

Comparison of bulk compositional data of basaltic meteorites of evolved asteroidal bodies and those of selected terrestrial volcanic rocks revealed important common thermal evolutionary trend of differentiating planetary bodies, regardless of their size. These trends were shown on Si normalized chemical element level bulk compositional fields of Fe/Mg, Ca/Al and Al/Mg and Al/Fe plots. On these compositional maps we focused on two differentiation sequences: one for achondrites, the other for the Earth. Both sequences spanned a wide range of Mg content. Achondritic sequence had higher total Fe content,. The higher Mg end of the sequences represented the earlier lava formations, the lower Mg containing basalts were the younger differentiates of the mantle. (Without fractionation the chondritic "clouds" of our dataset was found at higher total Fe contents, scattering around the chondritic average value of Mg/Si.)

The higher Fe content of achondritic sequence showed that the separation of Fe compounds on a smaller body (Vesta) could have not been so effective as on a larger body (Earth). Thickening of the crust resulted in lava gradually poorer in Mg as time advanced. Earlier high Mg containing komatiites were followed by later picrites and finally recent low-Mg lava on the Earth. Similarly, we could infer such a sequence of events on the differentiated asteroidal body, Vesta, too. First diogenitic, later howarditic and finally eucritic lava was there erupted onto the surface.

Al-rich phase separation from the mantle was the next period of differentiation, because of the lower density of aluminous minerals. Projections of these compositions onto the Al/Mg map showed parallel trends again both for achondrites and Earth, with lower Mg content of the corresponding achondritic basalts, because iron shared a part of the Mg/Fe mineralogical sites, and in the Earth's case these sites were partly occupied by Ca, too. Ca/Al plots showed that these two elements have been strongly correlated in bulk magmatic processes.

CONCLUSIONS

Comparison of bulk compositional data of basaltic meteorites of evolved asteroidal bodies and those of selected terrestrial volcanic rocks in our paper revealed an important common thermal evolutionary trend of a differentiating planetary bodies, regardless of their size.

The overview about the thermal evolution of a solid body, where the main trends in the basaltic volcanism were modeled gave the following conclusions. There were two types of segregations in planetary bodies: by gravitation and by melting. Partial melting helped segregation of first the metallic components which migrated toward the core. Second basaltic partial melts segregated and they moved toward the surface. Considering size, the early separation of the metal+sulfide bearing components was more effective on the large Earth, then in a small asteroid. The basaltic melts were first high MgO bearing types both on smaller asteroids and the larger Earth. Our comparisons showed that the main characteristics of the parallel evolution in the sequence of volcanic products: from the early high degree of partial melting komatiitic type (probably from a buried magma ocean) throughout the later, gradually lower degree of partial melting picritic type till the recent (on the Earth) stage differentiation of tholeiitic basalts. We conclude that this sequence is partly the result of the gradual separation of chemical elements - similarly to chemical separation according to the barometric height formula in the terrestrial atmosphere - in a gravitationally and thermodynamically affected Earth. We found a similarly MgO decreasing sequence of the diogenite-howardite-eucrite of basaltic achondrites from an evolved asteroid. This similarity indicates that time dependent changes in basalt volcanism have a size-independent scale parameter for different planetary bodies.

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