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Comparative geochemistry of basalts from the Moon, Earth, HED asteroid, and Mars: Implications for the origin of the Moon

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Abstract—Most hypotheses for the origin of the Moon (rotational fission, co-accretion, and collisional ejection from the Earth, including “giant impact”) call for the formation of the Moon in a geocentric environment. However, key geochemical data for basaltic rocks from the Moon, Earth, the howardite-eucrite-diogenite (HED) meteorite parent body (probably asteroid 4-Vesta), and the shergottite-nakhlite-chassignite (SNC) meteorite parent body (likely Mars), provide no evidence that the Moon was derived from the Earth, and suggest that some objects with lunar-like compositions were produced without involvement of the Earth. The source region compositions of basalts produced in the Moon (mare basalts) were similar to those produced in the HED asteroid (eucrites) with regard to volatile-lithophile elements (Na, K, Rb, Cs, and Tl), siderophile elements (Ni, Co, Ga, Ge, Re, and Ir), and ferromagnesian elements (Mg, Fe, Cr, and V), and less similar to those in the Earth or Mars. Mare and eucrite basalts differ in their Mn abundances, Fe/Mn values, and isotopic composition, suggesting that the Moon and HED asteroid formed in different nebular locations. However, previous claims that the Moon and HED parent body differ significantly in the abundances of some elements, such as Ni, Co, Cr, and V, are not supported by the data. Instead, Cr-Mg-Fe-Ni-Co abundance systematics suggest a close similarity between the source region compositions and conditions involved in producing mare and eucrite basalts, and a significant difference from those of terrestrial basalts. The data imply that the Moon and HED asteroid experienced similar volatile-element depletion and similar fractionation of metallic and mafic phases. Among hypotheses of lunar origin, rotational fission, and small-impact collisional ejection seem less tenable than co-accretion, capture, or a variant of giant-impact collisional ejection in which the Moon inherits the composition of the impactor. Both the Moon and HED asteroid may have been derived from a class of objects that were common in the early solar system. Copyright © 2001 Elsevier Science Ltd

“The most plausible model for the origin of the Moon in line with geochemical and cosmochemical constraints is an impact-induced “fission” of the proto-Earth.” —Wänke and Dreibus (1986)

“Clearly, the Moon and eucrite parent body resemble each other to a high degree. Nature produced such a composition not once but at least twice. This calls into question an entire class of models that invoke ad hoc processes to explain the Moon by a unique chance event.” —Anders (1977)

“The similarity between eucrites and lunar mare basalts are remarkable. Were it not for the differences in age and oxygen-isotope signature, it might be difficult to distinguish them on petrological or geochemical grounds.” —Taylor (1986)

1. INTRODUCTION

Although the origin of the Moon is still unresolved, the “giant-impact collisional ejection” hypothesis has been popular in the last decade. This has arisen not so much because of the merits of the hypothesis as because of the apparent dynamical or geochemical shortcomings of other theories (including intact or disintegrative capture of an independent planet, co-accretion or “double planet” formation, and fission of the Moon from a rapidly-spinning Earth; e.g., Wood, 1986; Stevenson, 1987; Taylor, 1992).

The giant-impact hypothesis postulates that the Moon formed from the ejecta of an immense collision between an

already-differentiated proto-Earth and “Mars-sized” impactor (e.g., Hartmann, 1986; Benz et al., 1987; Cameron, 1986, 1997; Newsom and Taylor, 1989). The Moon is derived from the outer portions of the proto-Earth and impactor, and would be impoverished in metal and siderophile elements if the impactor and proto-Earth had already differentiated (e.g., Melosh and Sonett, 1986; Wood, 1986; Cameron, 1997). Impact-induced vaporization and loss of volatile species to space could explain the depletion of volatile elements in the Moon compared to the Earth (e.g., Wood, 1986; Melosh and Sonett, 1986). If the Moon formed by a unique event, such as by a single giant impact, its composition might be expected to be unique. However, mass balance considerations (McFarlane, 1989) and dynamical models (e.g., Benz et al., 1986; A. G. W. Cameron, Harvard University, pers. comm., 1998) suggest that the proportion of impactor in the Moon would be high (50–100%). The lack of evidence for K-isotopic fractionation between the

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Moon and Earth also has been used to suggest that the composition of the Moon was inherited from the impactor (Newsom and Taylor, 1989), although it is unclear whether such isotopic fractionation would be expected following a giant impact (Stevenson, 1987; Taylor and Esat, 1996). If the Moon formed by a giant impact, any geochemical similarities between the Earth and Moon could be purely coincidental (Taylor, 1986; Newsom and Taylor, 1989).

Some workers accepted the premise of the giant-impact hypothesis and, on this basis, constructed elaborate chemical models for the composition, accretion, and core-forming history of the Moon and Earth (O'Neill, 1991a,b). However, other researchers noted that a giant impact introduces certain difficulties for differentiation models of the Earth, and questioned the plausibility of the model on these grounds (Ringwood, 1989a,b, 1990; Warren, 1992, 1998).

Other hypotheses involve forming the Moon more exclusively from terrestrial material. These include a variant of the giant-impact model proposed by Ringwood, here termed the "small-impact collisional ejection" model (e.g., Ringwood, 1986, 1989a,b, 1990). This model calls for the Moon to form out of ejecta from the Earth produced not by a single large impact, but rather from multiple impacts with smaller planetesimals. The "rotational fission" model (e.g., Binder, 1986) involves forming the Moon by fission from a rapidly spinning Earth. Both of these models postulate that the Moon is composed largely of material from the terrestrial mantle.

In various models, the Moon forms from a disk of material that surrounds the Earth. Such a disk could be produced by ejecta from large or small impacts on the Earth, or by collisions of heliocentric objects near the Earth (Weidenschilling et al., 1986; Herbert et al., 1986). Such a disk would allow "co-accretion" of the Moon. It also would have the potential to "compositionally filter" differentiated bodies in heliocentric orbits that pass through the disk, preferentially allowing the capture in the disk of disrupted silicate material, and allowing larger metallic core fragments to pass through the disk (Weidenschilling et al., 1986). This would be a variant of the "disintegrative capture" hypothesis of lunar origin.

The extent to which the Moon chemically resembles the Earth or other planetary bodies in the solar system is controversial. A possible chemical analog to the Moon is the howardite-eucrite-diogenite (HED) meteorite parent body. It has long been recognized that basalts from both the Moon (mare basalts) and HED parent body (eucrites) have similar abundances of many siderophile and volatile-lithophile elements, implying an overall chemical similarity between the mantles of these two objects (Tera et al., 1970; Taylor, 1975, 1986; Dreibus et al., 1977; Anders, 1977; Morgan et al., 1978; Taylor and Norman, 1990; Taylor and Esat, 1996).

In contrast, data for Ni and Co have been used to argue that the mantles of the Moon and Earth have similar Ni and Co abundances, and that the silicate portion of the HED asteroid is significantly more depleted in Ni and Co (Wänke et al., 1979; Wänke and Dreibus, 1986; Ringwood and Seifert, 1986; Ringwood, 1986, 1989a,b, 1990; Ringwood et al., 1990; O'Neill, 1991a). Similarly, the abundances of Cr, V, and Mn in various planetary materials have been used to argue for a chemical link between the Moon and Earth, and to suggest that the HED

parent body has a different abundance of these elements (Dreibus and Wänke, 1979; Wänke, 1981; Wänke and Dreibus, 1986, 1988; Ringwood, 1986, 1989a, 1990; Drake et al., 1989; Ringwood et al., 1990; O'Neill, 1991a). Low abundances of Cr, V, and Mn were inferred for both the Moon and Earth, and were attributed to the segregation of these elements into the Earth's core (Dreibus and Wänke, 1979, 1980; Wänke and Dreibus, 1986, 1988; Ringwood et al., 1990, 1991).

Published estimates of the model planetary abundances based on the work of Wänke and colleagues serve as a basis for discussion and are shown in Figure 1. Model abundances are normalized to Si and CI-chondrites for the silicate portions of the Moon, Earth, HED asteroid, and SNC parent body, with elements plotted in the order of decreasing nebular condensation temperatures (Wasson, 1985). Different types of samples (basalts, plutonic rocks, breccias, lunar soils) and methodologies (some complex) were used in the models for different objects. These models were summarized and critically evaluated by Ruzicka et al. (1998).

Four features of the models in Figure 1 are noteworthy. (1) All four planets are depleted relative to CI chondrites in volatile elements (elements ranging from P to Tl in condensation temperature). (2) Obvious anomalies occur for the siderophile elements Os, W, Ir, Ni, Co, Fe, Au, P and Ga, which have modelled depletions relative to elements of similar volatility. With regard to W, it is well-established that this element is depleted to roughly the same extent in the silicate portions of the Moon, Earth, and HED parent body, on the basis of relatively constant and similar W/La and W/U abundance ratios in samples from these objects (Wänke et al., 1973, 1977a; Palme and Rammensee, 1981; Wänke and Dreibus, 1986). (3) The Earth and Moon have nearly identical inferred depletions of Ni, Co, Cr, and Mn, in contrast to the HED asteroid, which is inferred to be much more depleted in Ni and Co, and much less depleted in Cr and Mn. (4) The Moon, Earth, and HED asteroid have similar, if not exactly identical, inferred depletions of V relative to elements of similar volatility. The model abundance of V in the HED asteroid (0.81 on a Si- and CI-normalized basis) is only slightly higher than that in the Moon (0.76) and Earth (0.71) (Dreibus and Wänke, 1980; Wänke, 1981), although Figure 2 of Wänke and Dreibus (1986) indicates a lower V value for the Moon. Model depletions of V for the Earth and Moon were attributed to the behavior of normally lithophile V as a siderophile element under reducing conditions and high pressure and temperature (Dreibus and Wänke, 1979, 1980; Wänke, 1981; Wänke and Dreibus, 1986; Ringwood et al., 1990, 1991), and were used to argue for the derivation of the Moon from the Earth's mantle (Wänke, 1981; Ringwood et al., 1990, 1991). However, the same could be said for the HED asteroid if the model abundance for V in the HED body (Fig. 1) is correct.

Based on these and similar models, it was concluded that the Moon formed largely out of impact ejecta from the Earth (Wänke and Dreibus, 1986; Ringwood, 1986, 1989a, 1989b, 1990; Ringwood et al., 1990). However, Ruzicka et al. (1998) used data for Ni, Co, Cr, V, and Mn in basalts from the Moon, Earth, and HED asteroid to argue instead that the models are flawed and that the data for these elements do not support either the giant-impact or small-impact collisional ejection hypotheses.

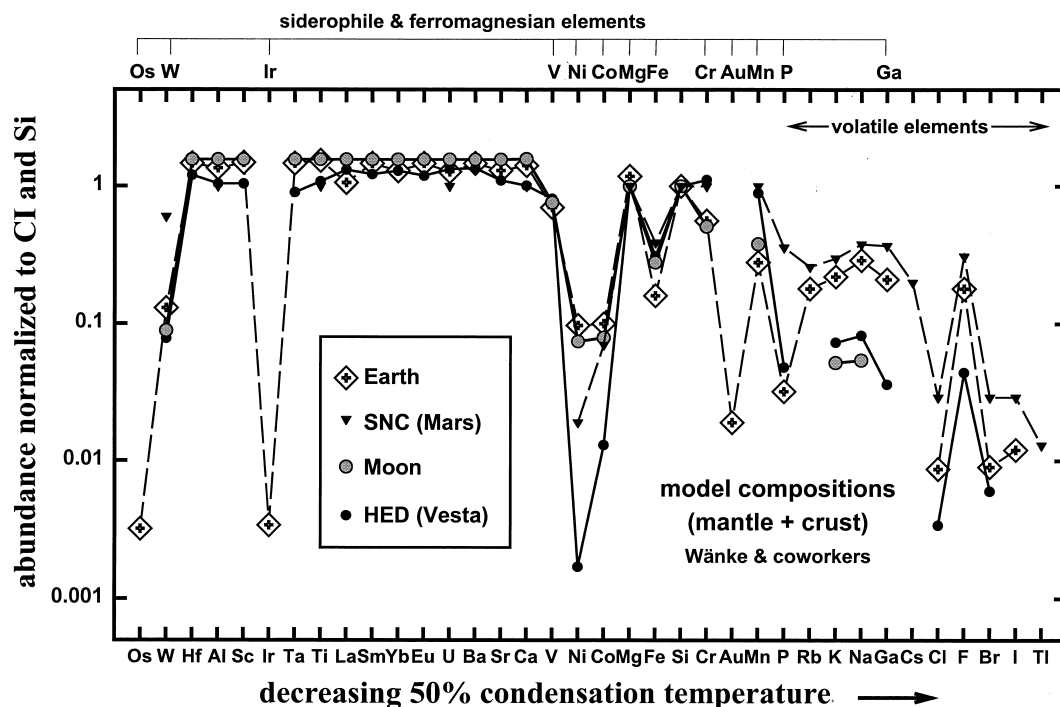


Fig. 1. Model compositions of the silicate portions of the Moon, Earth, SNC parent body, and HED parent body, based on the work of Wänke and colleagues (Wänke, 1981; Dreibus and Wänke, 1980; Wänke and Dreibus, 1988; Wänke et al., 1977a,b, 1978, 1979).

In this paper, geochemical data for mare basalts pertaining to the origin of the Moon are re-evaluated in the context of geochemical data for basaltic rocks from Earth, the HED parent body (probably the asteroid 4-Vesta; e.g., Gaffey et al., 1989; Binzel and Xu, 1993), and the SNC meteorite parent body (probably Mars; e.g., McSween and Treiman, 1998). Geochemical data for this “planetary basalt suite” are used to make a new assessment of what can, and what cannot, be reasonably inferred for the compositions of the source regions of the basalts. These source regions correspond to the mantles of the respective parent bodies and, potentially, to volumetrically large chemical reservoirs in these objects.

We interpret compositional data for elements representative of different geochemical groups characterized by large differences in partitioning behavior. The elements considered here include “refractory-lithophile” elements (La, Nd, U, and Ba), “volatile-lithophile” alkali elements (Na, K, Rb, Cs, and Tl), “siderophile” elements (Ni, Co, Ga, Re, and Ir), and “ferromagnesian” elements (Cr, V, Mn, Fe, and Mg). The refractory-lithophile and volatile-lithophile elements behave as highly incompatible elements in the presence of ferromagnesian mantle minerals (olivine, pyroxene, and spinel; Irving, 1978; Green, 1994; Beattie, 1994; Jones, 1995), but the two groups differ in their condensation temperatures in the solar nebula (Wasson, 1985) and in the ease with which they are vaporized. The ferromagnesian elements Cr, V, Mn, Fe, and Mg behave as compatible or semicompatible elements in the presence of ferromagnesian minerals (Irving, 1978; Green, 1994; Jones, 1995). Finally, the siderophile elements Ni, Co, Ga, Re, and Ir

have varying degrees of compatibility in ferromagnesian minerals, and partition strongly into metallic solids or liquids if such phases are present (Newsom, 1990; Jones, 1995; Green, 1994).

The magmatic processes influencing the compositions of the basaltic rocks were undoubtedly complex, and included some combination of partial melting, crystal settling, magma mixing, assimilation, convective processes occurring in magma chambers, and liquid immiscibility. It is beyond the scope of this paper to evaluate the importance of these processes for each element in detail. Nonetheless, we show that for these elements, relatively straightforward interpretations can be made that bear strongly on the origin of the Moon.

2. PLANETARY BASALT SUITE: SAMPLES AND DATABASE

In this paper, geochemical comparisons are made for basaltic rocks from different planetary bodies for a variety of elements key to constraining the origin of the Moon. We have compiled a chemical database that includes low-Ti mare basalts (<6 wt.% TiO₂), high-Ti mare basalts (6–14% TiO₂), eucrite achondrites, SNC achondrites, and terrestrial mafic and ultramafic rocks that originated at various times (Archean to Quaternary) and in a variety of tectonic settings. Data sources are listed in the Appendix. Eucrite and SNC data were taken largely from the compilations of Kitts and Lodders (1998) and Lodders (1998), respectively, although the database for eucrites was supplemented with other literature sources. Most of the data for mare basalts was taken from the compilation of Papike et al. (1998), although these too were supplemented with data from the literature.

Mare basalts are lunar flood basalts that are believed to have formed

Table 1. Comparison of major- and trace-element abundances (mean \pm standard deviation) for selected elements in basalts from various planetary bodies, including mare basalts from the Moon, non-cumulate eucrites from the HED asteroid, terrestrial basalts, and shergottites from the SNC parent body. In cases where the chemical variability is large, ranges are given in square brackets. Numbers in parentheses refer to the number of rocks.

	Low-Ti mare basalts ^a	High-Ti mare basalts ^a	Non-cumulate eucrites	Terrestrial basalts ^b	Shergottites
<i>Refractory incompatible elements</i>					
Ba $\mu\text{g/g}$	62.5 \pm 17.4 (68)	166 \pm 105 (55)	39.1 \pm 10.0 (22)	~250 [1–3000] (323)	16.4 \pm 11.8 (5)
La $\mu\text{g/g}$	6.80 \pm 6.21 (54)	11.6 \pm 8.3 (84)	3.35 \pm 1.10 (23)	~24 [0.7–238] (249)	0.785 \pm 0.649 (8)
Nd $\mu\text{g/g}$	12.8 \pm 4.09 (31)	43.7 \pm 18.7 (48)	6.44 \pm 2.18 (20)	~23 [0.1–176] (175)	2.13 \pm 1.11 (7)
U ng/g	189 \pm 74 (37)	322 \pm 284 (20)	128 \pm 38 (25)	~1000 [8–5700] (96)	51.7 \pm 43.9 (6)
<i>Ferromagnesian elements</i>					
Cr $\mu\text{g/g}$	3890 \pm 1340 (85)	2580 \pm 800 (87)	2450 \pm 610 (29)	~270 [1–1660] (276)	3680 \pm 2390 (8)
V $\mu\text{g/g}$	165 \pm 39 (36)	92.1 \pm 39.3 (84)	76.9 \pm 16.4 (17)	260 \pm 66 (180)	206 \pm 62 (8)
MnO mg/g	2.88 \pm 0.30 (87)	2.49 \pm 0.23 (88)	5.51 \pm 0.50 (28)	1.83 \pm 0.34 (333)	4.74 \pm 0.29 (8)
FeO wt% ^c	20.8 \pm 1.59 (82)	19.2 \pm 1.17 (88)	19.1 \pm 1.3 (29)	10.7 \pm 1.6 (336)	18.8 \pm 0.8 (8)
MgO wt%	10.4 \pm 3.0 (82)	8.23 \pm 1.28 (88)	7.16 \pm 1.09 (26)	7.55 \pm 2.32 (383)	16.1 \pm 8.5 (8)
<i>Siderophile elements</i>					
Ni $\mu\text{g/g}$	51.7 \pm 37.8 (61)	~12 [1–60] (23)	~7.1 [0.1–33] (25)	~110 [1–950] (317)	133 \pm 107 (7)
Co $\mu\text{g/g}$	47.8 \pm 14.3 (82)	20.9 \pm 6.2 (90)	6.13 \pm 2.39 (27)	42.7 \pm 10.0 (154)	48.3 \pm 18.0 (8)
Ga $\mu\text{g/g}$	4.06 \pm 0.98 (30)	6.61 \pm 1.54 (19)	1.61 \pm 0.29 (22)	20.3 \pm 3.4 (141)	14.3 \pm 6.5 (8)
Ge ng/g	8.40 \pm 6.81 (33)	~8 [1.5–32.5] (12)	~22 [0.7–80] (18)	1480 \pm 130 (8)	653 \pm 106 (4)
Re pg/g	~22 [0.4–360] (25)	~18 [0.7–31] (3) ^d	~9 [0.6–43.8] (13)	911 \pm 357 (8)	~372 [44–1020] (4)
Ir pg/g	~31 \pm 1.5–126] (31)	~37 [3–140] (12) ^d	~145 [0.46–620] (65)	~94 [0.4–734] (65)	2100 \pm 1520 (5)
<i>Volatile incompatible elements</i>					
Na mg/g	1.98 \pm 0.51 (87)	3.22 \pm 0.59 (88)	3.19 \pm 0.64 (26)	18.2 \pm 5.1 (330)	7.59 \pm 3.70 (8)
K mg/g	0.467 \pm 0.193 (78)	0.873 \pm 0.797 (89)	0.390 \pm 0.133 (23)	~5.4 [0.08–40.4] (399)	0.579 \pm 0.442 (8)
Rb $\mu\text{g/g}$	1.05 \pm 0.68 (46)	~1.94 [0.28–6] (25)	0.308 \pm 0.156 (21)	~17 [0.11–105] (327)	2.77 \pm 2.32 (6)
Cs ng/g	34.5 \pm 13.2 (26)	31.6 \pm 17.8 (6)	12.4 \pm 5.9 (21)	~840 [1–12000] (85)	185 \pm 156 (6)
Tl ng/g	~0.64 [0.06–7.0] (26)	[0.16–6.16] (12) ^d	1.41 \pm 1.28 (15)	~47 [6–280] (23)	7.6 \pm 3.8 (6)

Data sources listed in the Appendix.

^a Low-Ti \leq 5 wt.% TiO₂, high-Ti > 5 wt.% TiO₂.

^b Includes tholeiitic and alkali basalts from a variety of oceanic and continental settings and ranging in age from Archean to Tertiary.

^c All iron as FeO.

^d Haskin and Warren (1991).

by the partial melting of mantle cumulates that were produced in an early magma ocean, followed by varying degrees of near-surface fractional crystallization before eruption (e.g., Taylor, 1982; Warren, 1985; Hess, 1989; Taylor et al., 1991; Papike et al., 1998). There are two main types of mare basalts, low-Ti and high-Ti, that may have experienced different histories (e.g., Hess, 1989; Neal and Taylor, 1992; Papike et al., 1998).

Eucrites consist of brecciated and unbrecciated varieties, and non-cumulate and cumulate types (e.g., Basaltic Volcanism Study Project, 1981; Mittlefehldt et al., 1998). Of these, non-cumulate eucrites are petrographically the most similar to mare basalts; they could represent either primary partial melts or residual liquids (Stolper, 1977; Basaltic Volcanism Study Project, 1981; Mittlefehldt et al., 1998). There is increasing evidence that most or all eucrites formed by crystallization processes in an early magma ocean (Ikeda and Takeda, 1985; Warren and Jerde, 1987; Ruzicka et al., 1997; Righter and Drake, 1997; Barrat et al., 2000).

The SNC meteorites consist of a variety of lithologies, including basalts, lherzolites, clinopyroxenites, and one orthopyroxenite and one dunite (e.g., McSween and Treiman, 1998). Of these, the shergottites (especially the basaltic shergottites) are petrographically the most similar to mare basalts. Fractional crystallization and the incorporation of various proportions of cumulus phases appear to have been important in the formation of shergottites (McSween and Treiman, 1998).

The database for terrestrial rocks includes tholeiitic and alkali basalts from mid-oceanic ridges and oceanic islands (MORB and OIB); tholeiitic basalts, alkali basalts, and basaltic andesites from continental flood basalts and continental rifts; tholeiitic and calc-alkaline basalts from island arcs; and komatiites. The rocks in the terrestrial database

are representative of mafic and ultramafic volcanic rocks produced on Earth, especially in large igneous provinces. Reviews of the petrology of these rocks are given elsewhere (Basaltic Volcanism Study Project, 1981; Hess, 1989). For terrestrial basalts, partial melting at various depths in the Earth's mantle, low-pressure fractional crystallization, and assimilation of continental rocks have been identified as important processes (e.g., Basaltic Volcanism Study Project, 1981; Hess, 1989; Hooper, 1997; Saunders et al., 1997; Sharma, 1997; Lassiter and DePaolo, 1997).

The data presented in this paper include a minimal amount of "screening" to omit anomalous values. For example, anomalously high Tl values for some Antarctic eucritic meteorites (Paul and Lipschutz, 1990) were omitted; these may reflect weathering processes in the Antarctic environment. Anomalously high Ga abundances for mare basalts (Dickenson et al., 1989) were also excluded. In eucrites, brecciation may have allowed foreign material from projectiles to become incorporated in the meteorites, which could have had a major effect on trace-element abundances, particularly in the case of siderophile elements (e.g., Mittlefehldt et al., 1998). For these meteorites an attempt was made to exclude anomalously high abundance values for siderophile elements in cases where multiple splits were analyzed from the same meteorite.

Tables 1 and 2 show data for selected rocks in the database, including only those rocks that have lithologies that are the most similar to mare basalts, including non-cumulate eucrites, shergottites, and terrestrial tholeiitic and alkali basalts. Figure 2 shows average CI-normalized abundances of these rocks. Tables 1 and 2 and Figure 2 allow a broad comparison to be made of the compositions of basaltic rocks produced in four different parent bodies.

Table 2. Key abundance ratios (mean \pm standard deviation) of some element pairs in basalts from various planetary bodies. In cases where the chemical variability is large, ranges are given in square brackets. Rock types and data sources are the same as in Table 1.

	Low-Ti mare basalts	High-Ti mare basalts	Non-cumulate eucrites	Terrestrial basalts	Shergottites
<i>Volatile/refractory incompatible element ratios</i>					
wt/wt					
K/U $\times 10^{-3}$	2.60 \pm 0.90	3.89 \pm 1.97	3.42 \pm 1.33	~13 [2–102]	15.3 \pm 2.8
Rb/U	5.49 \pm 2.70	5.18 \pm 1.93	2.24 \pm 0.68	~36 [3–494]	56.0 \pm 11.3
Cs/U	0.210 \pm 0.073	0.317 \pm 0.156	0.0929 \pm 0.0321	~3 [0.1–78]	3.67 \pm 0.38
Tl/U $\times 10^3$	10.6 \pm 3.7	—	11.7 \pm 13.3	157 \pm 81	206 \pm 106
<i>Other element ratios</i>					
FeO/MnO ^a	72.7 \pm 9.0	77.7 \pm 9.1	34.8 \pm 3.0	59.5 \pm 9.2	39.9 \pm 2.53
Cr/V	24.3 \pm 6.3	30.8 \pm 13.0	31.7 \pm 8.6	~1.1 [0.1–8.6]	19.6 \pm 14.1
Cr/MgO $\times 10^4$	379 \pm 104	309 \pm 66	330 \pm 40	33.3 \pm 20.9	209 \pm 44
Ni/MgO $\times 10^4$	4.78 \pm 3.37	1.59 \pm 1.74	1.23 \pm 1.07	13.7 \pm 11.2	6.35 \pm 4.25
Co/MgO $\times 10^4$	4.75 \pm 1.41	2.55 \pm 0.69	0.897 \pm 0.292	6.11 \pm 2.10	3.33 \pm 0.71
Co/(MF) ^{a,b}	1.51 \pm 0.36	0.758 \pm 0.206	0.249 \pm 0.092	2.27 \pm 0.54	1.34 \pm 0.18

^a All iron as FeO.

^b Co/(MF) = Co/(MgO + FeO) $\times 10^4$.

3. RESULTS AND DISCUSSION

3.1. Incompatible, Refractory-Lithophile Elements (Ba, U, La, Nd)

Incompatible refractory-lithophile elements, including Ba, U, La and Nd, typically are enriched in basalts from all four of the parent bodies compared to chondrites (Figs. 2 and 3). On average, basalts from Earth are the most enriched, whereas those from Mars (shergottites) are the least enriched (Fig. 2). The average basalt from each object has a relatively flat chondrite-normalized abundance pattern for these elements (Fig. 2). For individual samples, abundance ratios for these elements

(Ba/La, Ba/U, La/Nd) vary around chondritic values (e.g., Wänke et al., 1973, 1977a). For example, Ba/La and Ba/U values vary to within a factor of 10, and mainly to within a factor of 2, of chondritic values (Fig. 3).

The approximately chondritic ratios of these elements are what one would expect if they were present in chondritic proportions in the parent bodies and if they were concentrated nearly equally into partial melts. Differences in overall abundance levels from one parent body to another probably reflect differences in igneous histories (e.g., different degrees of concentration in partial melts). In shergottites, the relatively low abundances of incompatible refractory-lithophile elements and

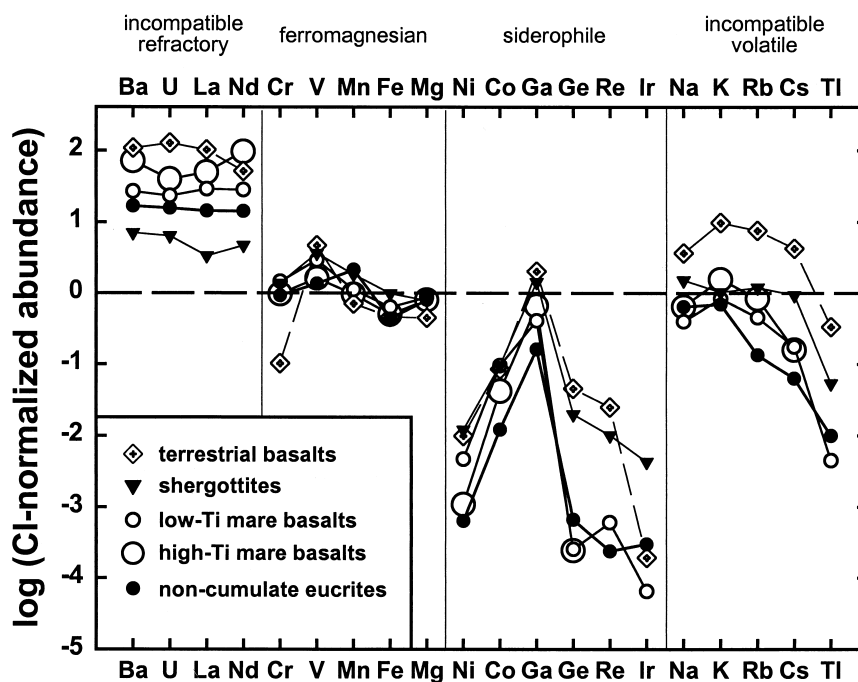


Fig. 2. Average CI-normalized abundances of key elements in various basalts. Data from Table 1.

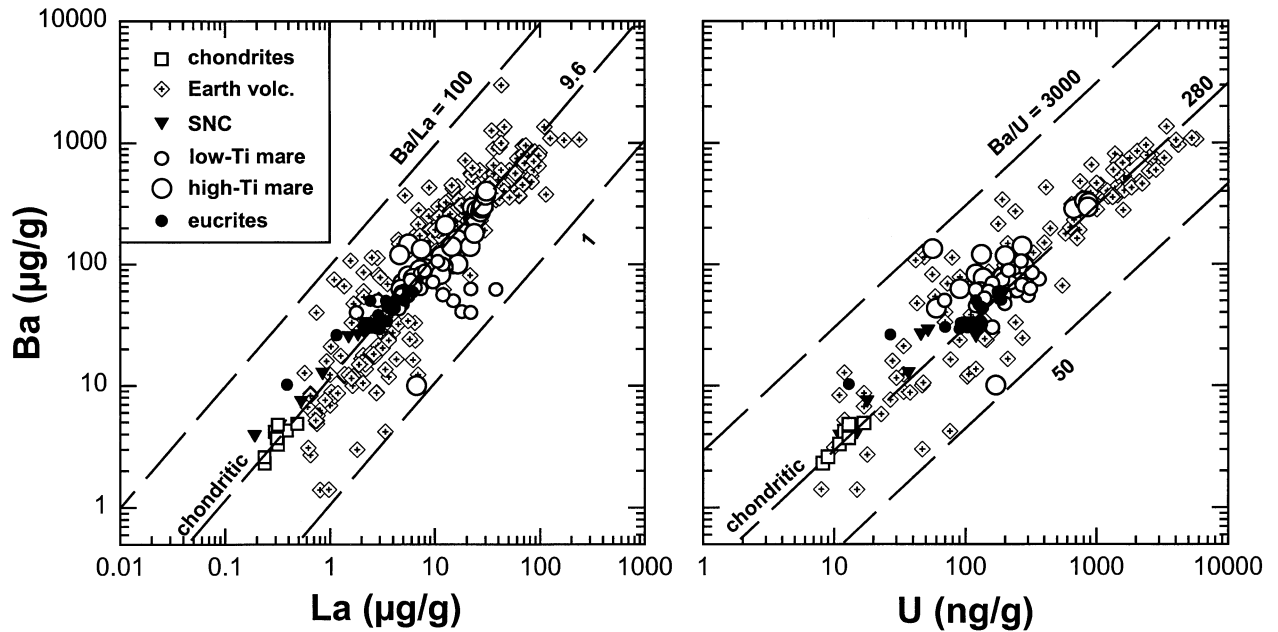


Fig. 3. The abundances of refractory-lithophile, incompatible elements (Ba-La and Ba-U) in the planetary basalt suite. Terrestrial samples include basalts, komatiites, and basaltic andesites. All basalts have roughly chondritic relative proportions of these elements. Data sources are given in the Appendix.

a relatively high abundance of Mg (Fig. 2), probably reflects the presence of mafic cumulus phases (olivine and pyroxene) in these meteorites (McSween and Treiman, 1998).

3.2. Incompatible, Volatile-Lithophile Elements (Na, K, Rb, Cs, Tl)

Incompatible volatile-lithophile elements, including the alkali elements Na, K, Rb, Cs, and Tl, have chondrite-normalized abundances that are lower than that of the refractory-lithophile elements in the same rocks, by a factor of ~ 10 to 1000 (Fig. 2). This difference represents a volatility-based fractionation. On average, chondrite-normalized abundances for these elements are highest in basalts from Earth, and lowest in mare basalts and eucrites (Fig. 2). Although the average absolute abundances vary from one object to another, the CI-normalized abundance patterns for these elements are similar, with Tl in all cases being the most depleted, and either K or Na being the least depleted, relative to chondrites (Fig. 2).

3.2.1. Sodium

Figure 4 shows that mafic and ultramafic volcanic rocks from each planetary body show relatively well-defined Na_2O -La trends. For the rocks from each body, the $\text{Na}_2\text{O}/\text{La}$ abundance ratio decreases as La content increases. Terrestrial mafic and ultramafic rocks form a trend that extends from chondrites to higher Na_2O and La; shergottites lie on or close to this same trend (Fig. 4). Mare basalts and eucrites form Na_2O -La trends that have similar slopes to the terrestrial rocks, but which are displaced to lower $\text{Na}_2\text{O}/\text{La}$ (Fig. 4). For a given La content, $\text{Na}_2\text{O}/\text{La}$ abundance ratios are a factor of ~ 6 to 7 lower for

mare basalts compared to terrestrial basalts, and are a factor of 3 to 4 lower for eucrites compared to terrestrial basalts (Fig. 4).

The pattern of soda-La variation shown by basaltic rocks is consistent with igneous fractionation processes, in which Na behaved as a moderately incompatible element, and La behaved as a highly incompatible element. Systematic differences in $\text{Na}_2\text{O}/\text{La}$ abundance ratios at a given La content imply that the basalt source regions on different parent bodies had different

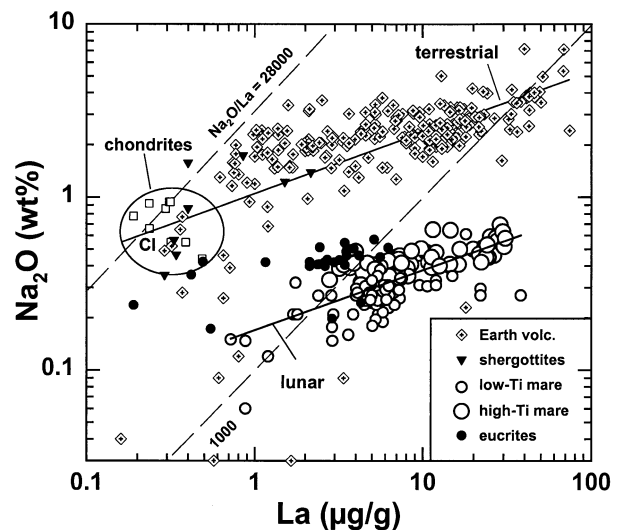


Fig. 4. Soda and La abundances in the planetary suite and chondrites. Terrestrial, lunar, and eucrite data points define arrays that are parallel and offset. Regression lines are shown for the terrestrial dataset and for the combined low-Ti and high-Ti mare basalt datasets. Data sources are given in the Appendix.

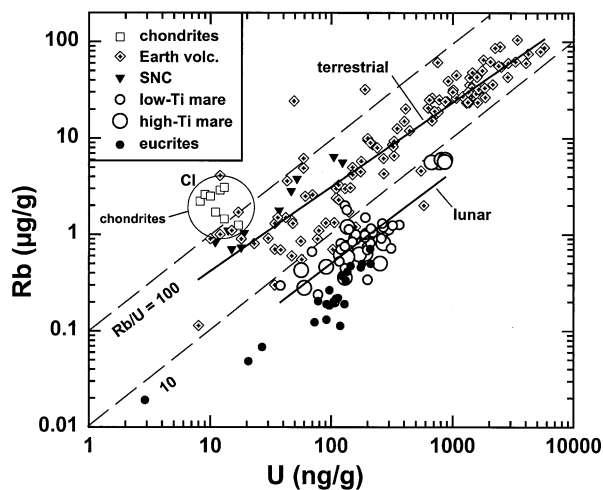


Fig. 5. Rb and U abundances in the planetary suite and chondrites. Terrestrial, lunar, and eucrite data points define arrays that are parallel and offset. Regression lines are shown for the terrestrial dataset and for the combined low-Ti and high-Ti mare basalt datasets. Data sources are given in the Appendix.

Na abundances, ranging from approximately chondritic for terrestrial volcanic rocks and shergottites, to subchondritic for mare basalts and eucrites. Extrapolating the Na-La trend for mare basalts (Fig. 4) to the La content of CI-chondrites yields an estimated depletion factor for Na in mare basalt source regions of ~ 7.5 , relative to CI-chondrites. Using the same procedure for eucrites yields a Na depletion factor of ~ 3 for these meteorites.

3.2.2. Potassium, rubidium, cesium, and thallium

The other alkali elements (K, Rb, Cs, Tl) also have abundances that are well-correlated with those of refractory lithophile elements. However, unlike Na, these elements show evidence for having behaved as highly incompatible elements during basalt genesis (e.g., Wänke et al., 1973), consistent with partitioning data (Irving, 1978; Green, 1994; Beattie, 1994).

Rb and U are well-correlated in the basalt suites (Fig. 5). In terrestrial mafic and ultramafic volcanic rocks, absolute abundances of Rb and U vary by 3 orders of magnitude, but Rb/U abundance ratios vary by a factor of 10 or less (Fig. 5). There is a tendency for the average Rb/U values to be higher in tholeiitic and alkali basalts from continental settings (~ 65) than from oceanic settings (~ 25). Rb/U values are relatively constant for the basaltic samples from a given planetary body (Fig. 5). Overall, there is a systematic difference in the average abundance ratios between different bodies, with Rb/U values decreasing in the order chondrites \geq SNC \geq terrestrial $>$ lunar \geq eucrites (Fig. 5).

The relatively constant Rb/U values in each basalt suite suggest that these elements were minimally fractionated compared to one another, and that both elements were highly incompatible during basalt genesis. There was, however, some fractionation of Rb from U on the Earth, as evidenced by the different Rb/U values in basalts from continental and oceanic settings. As refractory-lithophile elements have chondritic rel-

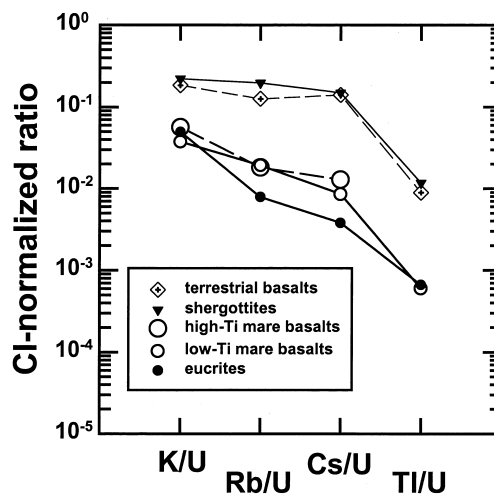


Fig. 6. Summary of average U- and CI-chondrite-normalized K, Rb, Cs, and Tl abundances in terrestrial basalts, mare basalts, shergottites, and eucrites. This plot reveals a strong similarity between eucrites and terrestrial basalts, and between average shergottites and terrestrial basalt composite (tholeiites and alkali basalts from continental and oceanic settings). Data from Table 2.

ative proportions (see above), the subchondritic Rb/U values in the basalts from each object imply that Rb is depleted in all of them. The difference in average Rb/U values implies that Rb abundances in the source regions decrease in the sequence SNC \geq terrestrial $>$ lunar \geq eucrites.

The abundances of other volatile-lithophile elements, such as K, Cs, and Tl, also are well-correlated with incompatible refractory-lithophile elements. As with Rb/U, values of K/U, Cs/U, and Tl/U are relatively constant in volcanic rocks from each parent body, compared to the extent to which K, Cs, Tl, and U were fractionated relative to chondrites. Once again, in the case of the Earth basalts, higher average K/U and Cs/U ratios are found from a continental setting (~ 19000 and ~ 11 , respectively) than from an oceanic setting (~ 10000 and ~ 0.3 , respectively). The large difference in Cs/U, almost two orders of magnitude, is especially notable. Apparent differences in alkali-element contents and Rb/Cs values for different chemical reservoirs on the Earth and their possible significance were noted and discussed previously (Hofmann, 1988; Kreuzberger et al., 1986; Wänke and Dreibus, 1986; O'Neill, 1991a,b; McDonough et al., 1992; Jones and Drake, 1993).

Table 2 shows average U-normalized abundances for the alkali elements (K, Rb, Cs, Tl), and Figure 6 shows average values of K/U, Rb/U, Cs/U, and Tl/U normalized to CI-chondrites, for terrestrial basalts (a composite of oceanic and continental tholeiites and alkali basalts), shergottites, low-Ti and high-Ti mare basalts, and non-cumulate eucrites. Normalizing the data to an incompatible refractory-element such as U has the effect of minimizing differences produced by igneous processes, because the incompatible refractory element serves as a monitor of the enrichment factor in partial melts (e.g., Anders, 1977). Normalizing the abundance ratios to CI-chondrites yields an estimate of the proportion of volatile elements in the basalt source regions compared to that of a standard solar composition (Anders and Grevesse, 1989).

The data reveal a strong overall similarity in volatile-litho-

phile element abundances between average eucrite, low-Ti mare basalt, and high-Ti mare basalt (Fig. 6, Table 2). In both mare basalts and eucrites, depletion factors relative to chondrites become progressively larger in the sequence K (~ 20), Rb (~ 50 to 125), Cs (~ 100 to 250), and Tl (~ 1700), in the order of expected volatility. The data also imply that volatile-element abundances are similar in average terrestrial basalt and shergottite (Fig. 6, Table 2). The similarity between terrestrial basalts and shergottites is partly coincidental, because the average values for terrestrial rocks depends on the number of basalts included in the average from continental and oceanic settings, and K/U, Rb/U, and especially Cs/U values differ between the two settings. Even so, the overall similarity between terrestrial basalts and shergottites is striking. In any case, it is clear that although all of the basalt source regions are depleted in K, Rb, Cs, and Tl compared to CI-chondrites, those in the Moon and HED asteroid are more depleted in these elements (by a factor of ~ 4 – 17) than those in the Earth and SNC parent body.

This reinforces the conclusion based on Na (see above) and in the literature (see Section 1) that the Moon and HED asteroid have similar and low abundances of volatile elements. Certainly with regard to the abundances of volatile alkali elements, the Moon has more in common with the HED asteroid than with the Earth.

3.3. Siderophile Elements (Ni, Co, Ga, Ge, Re, Ir)

Basaltic rocks from the Earth, Moon, HED asteroid, and Mars have variable, but generally low, CI-normalized abundances of siderophile elements (including Ni, Co, Ga, Ge, Re, and Ir; Fig. 2). Average abundances for all but Ga are $\sim 10^{-5}$ to $\sim 10^{-1} \times$ CI-chondrites, and those for Ga are ~ 0.1 to $2 \times$ CI-chondrites. For most siderophile elements, mare basalts and eucrites are the most depleted, and shergottites and terrestrial basalts are the least depleted (Fig. 2).

3.3.1. Nickel

Nickel has been regarded as key to an understanding of lunar origin by some researchers (see Section 1). Figure 7 shows the abundances of Ni and MgO in the basalt suite. Nickel and MgO abundances are positively correlated for terrestrial volcanic rocks (Hart and Davis, 1978; Basaltic Volcanism Study Project, 1981; Hess, 1989), low-Ti mare basalts (Wänke and Dreibus, 1986; Delano, 1986; Ringwood, 1986, 1990), lunar volcanic glasses (Delano, 1986), and (omitting one anomalous data point) shergottites (Wänke and Dreibus, 1988; Fig. 7). Terrestrial basalts and komatiites appear to form a nonlinear array, with Ni/MgO values decreasing at lower MgO abundances (Fig. 7; Basaltic Volcanism Study Project, 1981; Hart and Davis, 1978; Delano, 1986). Taken as group, low-Ti and high-Ti mare basalts and lunar volcanic glasses appear to define an overall nonlinear trend that resembles that of terrestrial rocks, but displaced to lower Ni/MgO values (Fig. 7). For a given MgO content, terrestrial volcanic rocks have a Ni/MgO value that is higher than that of mare basalts by a factor of ~ 5 to 10 (Fig. 7). Eucrites and high-Ti mare basalts have overlapping Ni and MgO contents (Fig. 7). These rocks vary more in Ni than in MgO content (Fig. 7).

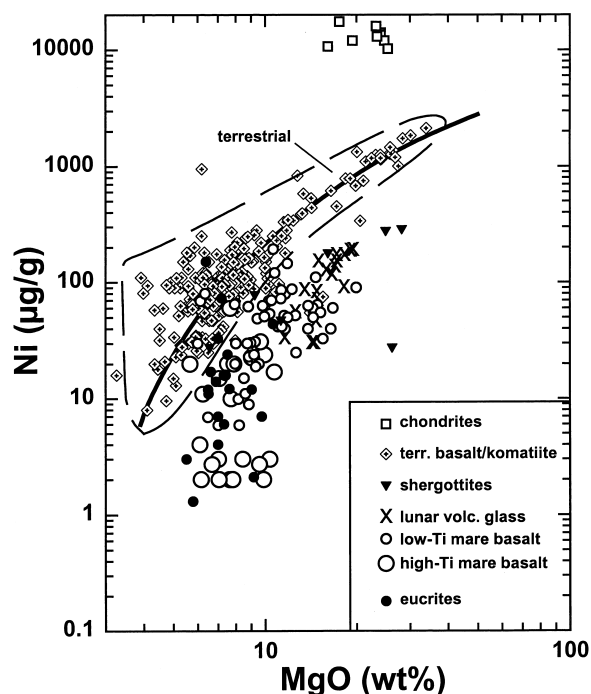


Fig. 7. Ni and MgO abundances in the planetary suite and chondrites. Terrestrial and lunar data points define arrays that are offset from one another, and eucrites have compositions that overlap the lunar array. Volcanic glass data for the Moon are from Delano (1986); other data sources are given in the Appendix.

The positive correlation between Ni and MgO abundances for terrestrial volcanic rocks, lunar volcanic glasses, and low-Ti mare basalts clearly indicates that Ni behaved as a compatible element during the formation of these basalts and glasses, consistent with partitioning data for olivine and pyroxene (Irving, 1978; Green, 1994; Jones, 1995). The nonlinear Ni-MgO array for terrestrial volcanics has been attributed (Hart and Davis, 1978; Basaltic Volcanism Study Project, 1981; Hess, 1989) to the temperature and composition dependence of olivine-melt Ni partitioning (Irving, 1978). In contrast, the pattern of Ni-MgO variation and low Ni contents for eucrites have been attributed to equilibration with (and presumably fractionation of) metal (Wänke and Dreibus, 1986; Ringwood and Seifert, 1986). Considering the overlapping Ni and MgO abundances of eucrites and high-Ti mare basalts (Fig. 7), metal fractionation also could be invoked for high-Ti mare basalts. However, considering that the compositions of high-Ti mare basalts appear to extend the trend shown by low-Ti mare basalts, and that the trend for mare basalts and lunar volcanic glasses as a group appears to mirror the terrestrial trend (Fig. 7), it is plausible that Ni abundances of high-Ti mare basalts were largely controlled by olivine partitioning. The processes controlling the compositions of eucrites are less certain, but the compositional similarity between eucrites and high-Ti mare basalts suggests that olivine fractionation may also have been important for eucrites. In any case, the source regions for eucrites, lunar basalts and lunar picritic glasses probably had lower Ni/MgO values than for terrestrial basalts, picrites, and komatiites.

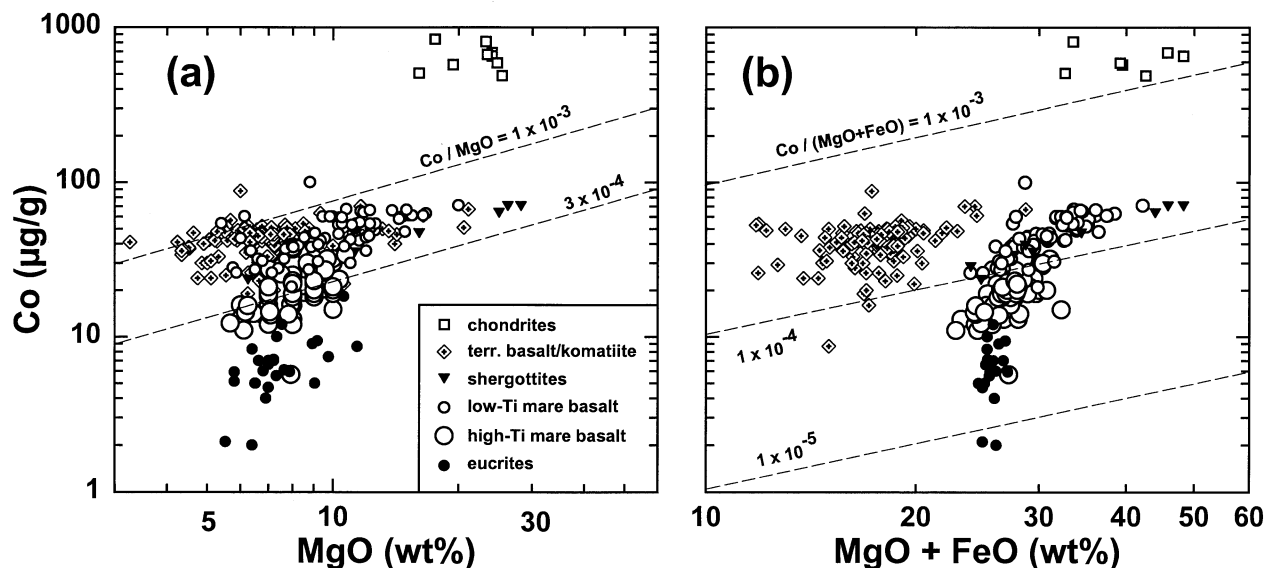


Fig. 8. Co abundance vs. (a) MgO abundance, and (b) (MgO + FeO) abundance for the planetary basalt suite and chondrites. In part (b), mare basalts, shergottites, and eucrites have compositions that form a continuous trend; terrestrial volcanic rocks are not part of this trend. Data sources are given in the Appendix.

The data shown in Figure 7 do not support the idea that the mantle of the HED parent body is depleted in Ni compared to that of the Moon (Wänke and Dreibus, 1986; Ringwood, 1990; cf. Newsom, 1986, 1990; Hewins and Newsom, 1988), or that the Ni content of the Moon closely resembles that of the Earth's mantle (Ringwood and Seifert, 1986; Ringwood, 1986, 1990; Wänke and Dreibus, 1986; Fig. 1). Instead, the case can be made that eucrites and mare basalts formed from magmas with similar initial Ni and MgO abundances and that these magmas differed significantly in composition from terrestrial magmas.

Nickel-MgO abundance systematics for all of the basalts can be explained by a two-step process, assuming that the basaltic magmas were derived from sources that were initially chondritic in composition. The first step would be the sequestering of Ni in a metallic phase, which depleted magmas in Ni, but not in MgO, before basalt formation. The magnitude of Ni depletion caused by metal removal can be inferred by the difference in Ni content between chondrites and komatiites and picritic lunar glasses with similar MgO abundances (Fig. 7). Metal segregation decreased Ni contents in terrestrial systems by a factor of ~ 20 , and in lunar (and possibly eucritic) systems by a factor of ~ 100 . The second step was olivine fractionation before or during basalt formation, which decreased Ni and MgO abundances simultaneously to produce the compositional arrays observed for the terrestrial basalts, low-Ti mare basalts, and lunar picritic glasses (Fig. 7). Additional olivine fractionation, and possibly fractionation of other phases such as pyroxene or additional metallic phases, decreased Ni in magmas still further to produce high-Ti mare basalts and eucrites (Fig. 7). In this model, high-Ti mare basalts and eucrites both represent magmas that fractionated a substantial quantity of olivine, and low-Ti mare basalts represent magmas that fractionated less olivine. The lunar and eucritic magmas were depleted in Ni by a factor of ~ 5 to 10 compared to terrestrial magmas at a similar stage of olivine fractionation.

3.3.2. Cobalt

Cobalt also has been regarded as key to understanding the Moon's origin by some researchers (see Section 1). Figure 8a shows a Co-MgO plot in analogy with that of Figure 7, and Figure 8b shows the variation of Co with (MgO + FeO), in a diagram that has been used by others (Wänke et al., 1979; Wänke and Dreibus, 1986, 1988; Ringwood and Seifert, 1986; Ringwood, 1989a).

Volcanic rocks that have MgO abundances and (MgO + FeO) values similar to that of chondrites are depleted in Co relative to chondrites by a factor of ~ 10 (Fig. 8). Abundances of Co and MgO are positively correlated for each basalt suite (Fig. 8a), and abundances of Co are correlated with (MgO + FeO) for low-Ti mare basalts, high-Ti mare basalts, and shergottites (Fig. 8b). Cobalt/(MgO + FeO) values are relatively constant only for low-Ti mare basalts and shergottites, but even for these rocks, Co/(MgO + FeO) values decrease slightly as (MgO + FeO) decreases (Fig. 8b). In contrast, eucrites have nearly constant (MgO + FeO) values but variable Co abundances (Fig. 8b). High-Ti mare basalts are intermediate to eucrites and to low-Ti mare basalts (and shergottites) both in terms of Co and (MgO + FeO) values and in the pattern of variation between these parameters (Fig. 8b). As a result, there is a continuous compositional trend between low-Ti mare basalts, shergottites, high-Ti mare basalts, and eucrites in terms of Co and (MgO + FeO) values (Fig. 8b). In contrast, terrestrial basalts are not part of this trend and are distinct from other basaltic samples in having low (MgO + FeO) values (Fig. 8b). This reflects the distinctly low iron abundances in terrestrial basalts compared to other basalts (Table 1).

The positive correlations between Co and MgO abundances (Fig. 8a) imply that Co behaved as a compatible or semicompatible element during basalt formation in each rock suite, consistent with partitioning data for olivine and pyroxene (Irv-

ing, 1978; Green, 1994; Beattie, 1994; Jones, 1995). However, differences in the slopes of the trends in Figure 8a,b suggest that the compatibility of Co was not the same in all systems and that it varied systematically for extraterrestrial systems. During the genesis of low-Ti mare basalts and shergottites, the compatibility of Co was relatively low, and intermediate to that of MgO and FeO, as evidenced by the relatively constant Co/(MgO + FeO) values in these rocks (Fig. 8b). The compatibility of Co was progressively higher during the formation of high-Ti mare basalts and eucrites, resulting in steeper trends in Figure 8a,b.

Most significant, the continuity of the Co-(MgO + FeO) trends shown by eucrites, high-Ti mare basalts, low-Ti mare basalts, and shergottites (Fig. 8b) is suggestive of compositional evolution of magmas that had similar initial MgO, FeO, and Co abundances. Systematic changes in the pattern of Co-MgO and Co-(MgO + FeO) variation for these basalts can be explained if Co behaved as an increasingly compatible element at progressively lower temperature, as magmas evolved to lower MgO abundances and lower values of (MgO + FeO) by the fractionation of ferromagnesian phases. This interpretation is supported by partitioning data for olivine and pyroxene, which indicate that D -values for both phases increase with decreasing temperature (Irving, 1978). Thus, the continuous Co-(MgO + FeO) trend for mare basalts, eucrites, and shergottites (Fig. 8b) could have been produced by fractionation of olivine and/or pyroxene.

As was the case for Ni, a two-step process can best explain the data for Co in these samples. The first step was segregation of metal, which accounts for the Co depletion of picritic lunar basalts and shergottites relative to chondrites. The second step was fractionation of ferromagnesian phases (in this case, olivine and/or pyroxene) to produce the range of compositions in shergottites, mare basalts, and eucrites. In this model, eucrites experienced the greatest fractionation of ferromagnesian minerals, high-Ti mare basalts the next greatest fractionation, and shergottites and low-Ti mare basalts the least. Similar processes could have affected the source regions of terrestrial basalts, but the reason for the lower FeO abundances and the greater compositional scatter for these rocks (Fig. 8b) is not obvious.

The data shown in Figure 8 do not support the idea that the mantles of the Moon and Earth have similar Co abundances and that the HED asteroid has a significantly different Co abundance (Wänke, 1981; Wänke and Dreibus, 1986; Ringwood and Seifert, 1986; Ringwood, 1986, 1990; Newsom, 1986; Hewins and Newsom, 1988; Fig. 1). Instead, it appears that the Earth is anomalous compared to other planetary bodies in having especially iron-poor basalt source regions, and that extraterrestrial basalts from the Moon, Mars, and HED asteroid could have originated in source regions that had similar initial abundances of Co. Although it is true that Co/(MgO + FeO) values for terrestrial basalts and low-Ti mare basalts are similar and distinctly higher than for eucrites (Wänke and Dreibus, 1986; Ringwood, 1986, 1989a; Ringwood and Seifert, 1986), this ignores the possibility that magmatic fractionation could change these values. High-Ti mare basalts, which have Co, MgO, and FeO abundances and Co-MgO and Co-(MgO + FeO) trends intermediate to that of eucrites and low-Ti mare basalts (Fig. 8 and Tables 1 and 2), provide strong support for the idea that magmatic fractionation did, in fact, change Co/

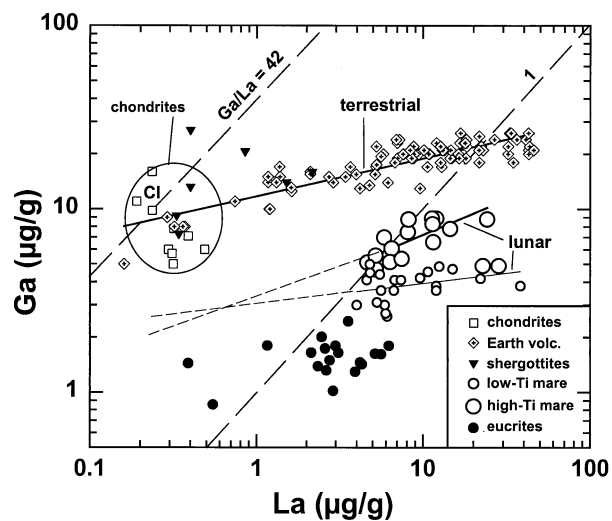


Fig. 9. Ga and La abundances in the planetary basalt suite and chondrites. Data points for terrestrial basalts and mare basalts show subparallel trends, with what appears to be two separate trends for the mare basalts. Data sources are given in the Appendix.

(MgO + FeO) values. The compositions of high-Ti mare basalts “bridge the gap” between that of eucrites and other extraterrestrial basalts, and suggest that differences in Co/(MgO + FeO) values between different basalts were caused by systematic changes in the Co partition coefficient during magmatic evolution.

3.3.3. Gallium

Among the siderophile elements considered here, Ga has the least siderophile tendency (Newsom, 1990; Jones, 1995). This fact probably explains the relatively high CI-normalized abundances of Ga compared to other siderophile elements (Fig. 2). Gallium is also a relatively volatile element (Fig. 1).

Figure 9 shows the abundances of Ga and La in the planetary basalt suite. A similar diagram was used by Drake (1983) to constrain the origin of the Moon, and by Drake et al. (1984) and Malvin and Drake (1987) to study basalt formation in the Earth, Moon, and HED asteroid. Terrestrial basalts and komatiites, and low-Ti mare basalts, show well-defined and similar Ga-La trends (Fig. 9). However, for a given La content, low-Ti mare basalts are displaced to lower Ga abundances by a factor of ~ 5 compared to terrestrial basalts (Fig. 9). High-Ti mare basalts appear to define a separate correlation line, although two older analyses for Ga in high-Ti mare basalts (Wasson and Baecker, 1970) fall closer to the low-Ti mare basalt correlation line (Fig. 9). Omitting these two data points, which may be in error, the correlation line for high-Ti mare basalts is steeper than that for low-Ti mare basalts (Fig. 9). Shergottites have Ga and La abundances that fall close to the terrestrial correlation line, and eucrites have Ga abundances that are lower than that of mare basalts (Fig. 9). The data points for eucrites and shergottites scatter, but those for eucrites have an overall Ga-La trend similar to that of lunar and terrestrial basalts (Fig. 9).

The Ga-La correlations imply that Ga behaved as a moderately incompatible during basalt genesis in the rock suites,

consistent with partitioning data in silicate systems (Malvin and Drake, 1987; Green, 1994; Jones, 1995). The correlation line for terrestrial volcanic rocks passes close to CI-chondrites, and the compositions of komatiites and shergottites overlap those of chondrites (Fig. 9). If La abundances were initially chondritic, it follows that the source regions for terrestrial basalts and shergottites had roughly chondritic Ga abundances. There is little doubt that the source regions for mare basalts and eucrites were depleted in Ga compared to those of terrestrial basalts and chondrites (Drake, 1983; Drake et al., 1984), although there is some uncertainty as to whether the Earth's mantle is depleted in Ga compared to chondrites (Drake et al., 1984).

The apparent existence of two distinct Ga-La trends for low-Ti and high-Ti mare basalts (Fig. 9) is notable. This could be explained by differences in source region Ga abundances, but the different slopes for the Ga-La trends suggest that the compatibility of Ga was not identical during the formation of these basalts. Mineral/melt D -values for Ga differ for olivine, clinopyroxene, plagioclase, and spinel (Malvin and Drake, 1987), so variations in the proportions of these (and other) phases left behind as solid residues during partial melting would result in differences in the bulk partition coefficient of Ga. The extrapolated best-fit correlation lines for low- and high-Ti mare basalts intersect at ~ 6 ppm La and ~ 2.5 ppm Ga (Fig. 9). This is a plausible source region composition for both types of mare basalts, involving depletion in Ga and enrichment in La relative to chondrites. The latter enrichment is consistent with the depletion of volatile-lithophile elements in mare basalt source regions (see above, and Section 1). Thus, the data for mare basalts can be interpreted as indicating that low-Ti and high-Ti mare basalts originated in separate source regions that had similar initial Ga and La abundances, but which evolved differently during basalt formation.

The apparent depletion of Ga in the source regions of mare basalts and eucrites compared to terrestrial basalts and shergottites can be interpreted in one of two ways. Either the difference is another manifestation of greater volatile-element depletions in the Moon and HED asteroid, or it is another manifestation of a greater fractionation of metallic phases (solid metal or S-bearing metallic melt) in the mare basalt and eucrite source regions. With regard to the latter possibility, it is important to note that metallic phases would have had to segregate prior to basalt formation, for otherwise Ga would not have behaved as a moderately incompatible element during basalt formation. Regardless of the process responsible for the Ga depletion in mare basalts and eucrites, it is evident that Ga abundances were distinctly low in basalt source regions for the Moon and HED asteroid compared to those in the Earth and SNC parent body. This does not support the case for a unique chemical link between the Moon and Earth.

3.3.4. Germanium, rhenium, and iridium

Ge, Re, and Ir partition strongly into metallic solids and liquids (Newsom, 1990; Jones, 1995). Together with Ni, these elements have the highest D -values for partitioning between solid or liquid metal and liquid silicate ($D^{SM/LS}$ and $D^{LM/LS}$) (Newsom, 1990; Jones, 1995). They also have the lowest CI-normalized abundances (Fig. 2). This suggests that the fractionation of metallic solids or liquids was largely respon-

sible for establishing the low abundances of these and other highly siderophile elements in the basalts (Drake, 1983; Newsom, 1986, 1990; Hewins and Newsom, 1988).

Although data for Ge and Re are comparatively sparse, large differences in Ge and Re abundances occur between mare basalts and eucrites on the one hand, and terrestrial basalts and shergottites on the other (Fig. 2, Table 1). Mare basalts and eucrites have overlapping Ge abundances (~ 1 –80 ng/g), which are significantly less than in shergottites (~ 650 ng/g) and terrestrial basalts (~ 1.5 $\mu\text{g/g}$; Table 1), and which are three to five orders of magnitude less than in chondrites (~ 7 –50 $\mu\text{g/g}$) (Wasson and Kallemeyn, 1988). Similarly, Re abundances in mare basalts and eucrites (typically 1–50 pg/g) are significantly less than in shergottites (~ 370 pg/g) and terrestrial basalts (~ 900 pg/g; Table 1), and three to five orders of magnitude less than in chondrites (~ 30 –80 ng/g) (Wasson and Kallemeyn, 1988).

The D -value for partitioning of Ge between solid and liquid silicate ($D^{SS/LS}$) in experimental systems, and inferred for basalt formation in the Earth, is of order unity (Malvin and Drake, 1987), whereas the value for partitioning between metallic solids and silicate melt ($D^{SM/LS}$) and between metallic liquids and silicate melt ($D^{LM/LS}$) is much greater than unity (Newsom, 1990). This suggests that CI-normalized abundances of Ge in basalts (Fig. 2) can be taken as a measure of the extent to which metal was depleted in the source regions, assuming initial chondritic abundances of Ge. The implied magnitude of the Ge depletion in the source regions increases in the order Earth \leq Mars $<$ Moon \sim HED asteroid.

In contrast to Ge, there is evidence that the behavior of Re in terrestrial magmatic systems was complex, ranging from incompatible during the formation of komatiites, to compatible during the formation of mid-oceanic ridge basalt (MORB) and oceanic island basalt (OIB) (Warren and Kallemeyn, 1996; Righter and Hauri, 1998). Rhenium may have behaved as a compatible element in the formation of mare basalts and eucrites (Birck and Allegre, 1994) and, to a lesser extent, in shergottites (Birck and Allegre, 1994; Warren et al., 1998). The lower Re abundances in mare basalts and eucrites compared to shergottites and terrestrial rocks has been attributed (Birck and Allegre, 1994) to lower $f\text{O}_2$ on the Moon and HED parent body, which may have caused Re to behave as a more compatible element in the Moon and HED parent body compared to Earth. Alternatively, pressure-related effects may have been important for Re partitioning in the Earth (Righter et al., 1997), and less so for the Moon and HED parent body.

Iridium has been called the "type siderophile element" owing to its strong siderophile tendency (Haskin and Warren, 1991). Average CI-normalized Ir abundances are similar in mare basalts, eucrites, and terrestrial basalts; by comparison, shergottites have higher abundances (Fig. 2). Although the average Ir abundance in eucrites is slightly higher than in terrestrial basalts (Table 1, Fig. 2), this is probably misleading. Lower Ir abundances (~ 4 –25 pg/g) occur in non-brecciated eucrites (Ibitira and ALH 81001) than in brecciated eucrites (up to 620 pg/g), suggesting that eucrites were widely contaminated during the brecciation process that affected most of them, and that the indigenous Ir abundance in eucrites is closer to ~ 4 to 25 pg/g. Recent, high-quality data indicate that eucrites are typi-

cally more depleted in Ir and other highly siderophile elements compared to mare basalts (Warren, 1999).

The abundance of Ir is correlated with that of MgO and Ni in terrestrial basalts and komatiites (Brügmann et al., 1987, 1993; Warren et al., 1998; Rehkämper et al., 1999), in shergottites and mare basalts (Warren et al., 1998), and in eucrites (Warren, 1999). The Ir-MgO correlation is nonlinear and resembles the Ni-MgO pattern (Fig. 7) (Warren et al., 1998). Evidently, Ir behaved as a compatible element during basalt formation in various planets. Ni/Ir abundance ratios are relatively constant in mare basalts, eucrites, and terrestrial basalts, despite evidence for differing degrees of Ni depletion (Warren, 1999; greater in lunar and eucritic basalt source regions, and less in terrestrial basalt source regions; see above). These observations can be explained by the fractionation to differing extent of one or more siderophile-rich phases that had a similar Ni/Ir value in the Moon, HED asteroid, and Earth.

Overall, the data for Ir, Ge, and Re diminish support for a unique chemical link between the Moon and Earth. Germanium abundances in the basalt source regions of the Moon and HED asteroid were similar, and much more depleted than those in the Earth. Rhenium abundances and partitioning behavior during basalt formation in the Moon and HED asteroid were similar, and unlike that of the Earth. Finally, similar Ni/Ir values and overlapping Ir-MgO trends for lunar, terrestrial, and eucritic basalts cast further doubt on models that postulate unique conditions for forming the Moon (Warren et al., 1998; Warren, 1999).

3.4. Ferromagnesian Elements (Cr, V, Mn, Fe, Mg)

Average ferromagnesian element abundances for the basalts range within a factor of ten of CI-chondrite values (Fig. 2). Three aspects of these data are notable. (1) Terrestrial basalts are depleted in Cr compared to other basalts by an order of magnitude (Fig. 2, Table 1). This is in stark contrast to the planetary abundance models of Wänke and coworkers (Fig. 1) and Ringwood, which postulate Cr depletions in the Moon that are similar to or larger than that in the Earth (Dreibus et al., 1979; Wänke and Dreibus, 1986; Ringwood, 1989a; Ringwood et al., 1990, 1991). (2) Terrestrial basalts have a low iron content (10.7 ± 1.6 wt.% FeO) compared to other basalts (~ 18 – 22 wt.% FeO) (Table 1). This low iron content was mentioned above in connection with producing low values of (MgO + FeO) for terrestrial basalts, with the result that terrestrial data plot in an otherwise unpopulated region of the Co and (MgO + FeO) diagram (Fig. 8b). (3) Shergottites have the highest MgO contents (Table 1). This probably reflects the high proportion of Mg-rich cumulus olivine or pyroxene in some shergottites (McSween and Treiman, 1998).

As noted in the Introduction, abundance data for Cr, V, and Mn have played an important role in previous models for the origin of the Moon. Below, data for each of these elements are discussed separately.

3.4.1. Chromium

Fig. 10 shows Cr abundance plotted against Mg# (= atomic Mg/(Mg + Fe)) for mare basalts, eucrites, SNC meteorites, and terrestrial volcanic samples. Each rock suite defines distinct

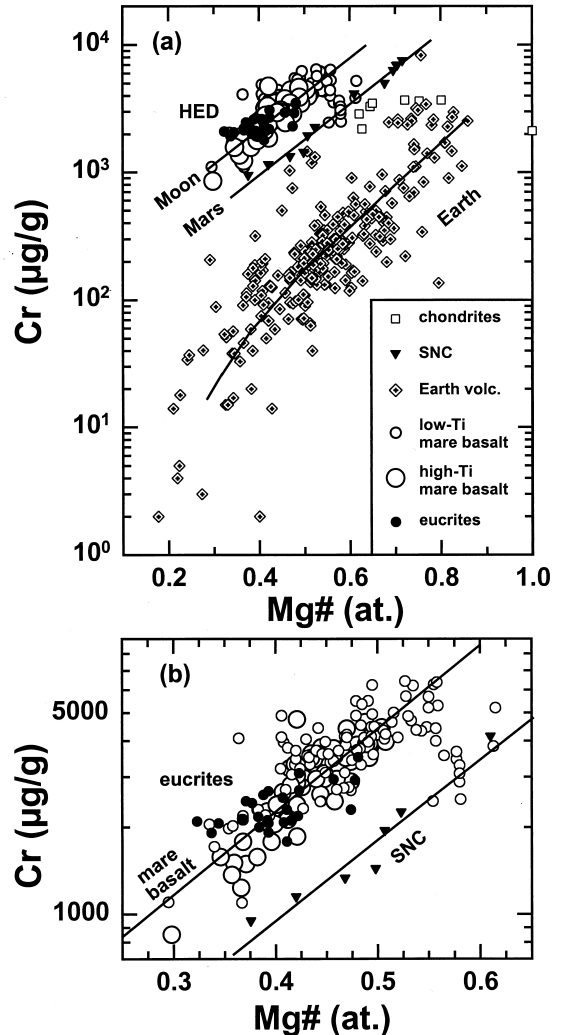


Fig. 10. Cr abundance plotted against Mg# (= Mg/(Mg + Fe), atomic) in the planetary basalt suite and chondrites, showing (a) all data and (b) a close-up of mare basalts and eucrites. The basalts from all four bodies show well-defined trends, but differ in their Cr/Mg values (Table 2). Eucrite data points plot with those of high-Ti mare basalts. Linear regressions are shown for the SNC and mare basalt data; the trend shown by the Earth is schematic. Data sources are given in the Appendix.

compositional arrays characterized by positive correlations between Cr abundance and Mg# value, although neither parameter varies much for eucrites (Fig. 10). Parallel data arrays are observed for mare basalts, SNC meteorites, and terrestrial volcanic rocks (Fig. 10a), with the compositions of eucrites overlapping those of high-Ti mare basalts (Fig. 10b). For a given Mg# value, Cr abundance is highest for mare basalts and eucrites, intermediate for SNC meteorites, and lowest for terrestrial volcanic rocks (Fig. 10a). Average values of Cr/Mg decrease in the same sequence (Table 2). For a given Mg# and Mg content, terrestrial volcanic rocks generally have one to two orders of magnitude lower Cr abundance than mare basalts or eucrites.

The positive correlations between Cr abundance and Mg# and Mg content for all of the rock suites suggests that Cr

behaved as a compatible element during basalt genesis. The slopes of the trends in Figure 10 are similar for each of objects, except at low values of Mg# for terrestrial rocks. The parallel trends suggest that the bulk Cr mineral-melt partition coefficient was the same for these basalts, and that it was almost constant over a large range of Mg# and Cr abundances.

It has been suggested that Cr was better able to partition into spinel and clinopyroxene in the Earth, where conditions were more oxidizing, than in the Moon and HED parent body, where conditions were more reducing, and that this could explain differences in basalt Cr contents (Papike and Bence, 1978; Basaltic Volcanism Study Project, 1981, pp. 321–326). Although this effect cannot be discounted, it implies differences in Cr compatibility from one object to another that should not result in parallel data arrays. Instead, it seems more likely that Cr abundances were already different in the source regions at the time of basalt formation.

If one assumes that Cr abundances and Mg# values of the basalt source regions were originally chondritic, one can make inferences regarding how different basalts could have obtained different Cr abundances and Mg# values. Mare basalts and eucrites have Cr abundances similar to, and Mg# values lower than, those of chondrites (Fig. 10a). In contrast, terrestrial volcanic rocks typically have subchondritic Cr abundances and Mg# values that range up to chondritic (Fig. 10a). Clearly, the two sets of objects were different, with SNC meteorites being intermediate between the two. The data for mare basalts and eucrites could be explained if the source regions for these basalts experienced an early fractionation that mainly lowered the Mg content of the melt, followed by a fractionation that produced correlated changes in Cr and Mg abundances. In contrast, the data for terrestrial rocks suggest that their source regions experienced Cr depletion, followed by a fractionation that produced correlated changes in Cr and Mg contents of the magma. The magma ocean model of Ruzicka et al. (1997) for the HED asteroid yields a compositional trajectory for eucritic magma that virtually reproduces the Cr-Mg# values of mare basalts and eucrites from an originally chondritic source composition. In this model, early fractionation of olivine, orthopyroxene, and minor chromite mainly decreases Mg#, whereas later fractionation of pigeonite produces a correlated Cr-Mg# array.

In any case, basaltic magmas in the Moon and HED asteroid were compositionally distinct from those in the Earth. Based on Cr-Mg-Fe abundance systematics, it appears that the Moon and HED asteroid basalt source regions (1) could have had similar initial compositions, (2) formed in broadly similar ways, and (3) experienced magmatic fractionation under similar conditions (e.g., low fO_2). In contrast, the source regions of terrestrial basalts evolved differently. These conclusions are inconsistent with the prevailing idea that Cr is significantly depleted in the Moon compared to the HED parent body, and they provide no reason to believe that the Earth and Moon have especially similar Cr contents (Fig. 1; see Section 1).

3.4.2. Vanadium

Figure 11 shows the abundances of V and Cr in the rock suites. It has long been known that the abundances of V and Cr are correlated in lunar mare and highland samples (Laul et al.,

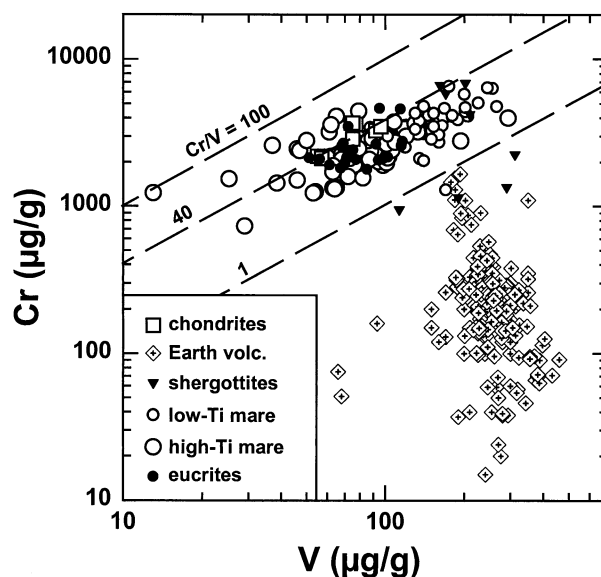


Fig. 11. Cr and V abundances in the planetary basalt suite and chondrites. Data sources are given in the Appendix.

1972a; Wänke et al., 1978). Figure 11 demonstrates that the abundances of V and Cr co-vary in mare basalts and eucrites, but that these elements do not correlate in terrestrial volcanic rocks or in shergottites (Fig. 11). Mare basalts and eucrites have overlapping compositions, with V and Cr contents ranging from chondritic to somewhat lower Cr/V values. By contrast, terrestrial volcanic rocks have higher V but significantly lower Cr abundances, and significantly lower Cr/V values (Fig. 11 and Tables 1 and 2). On average, Cr/V values decrease in the order chondrites \geq eucrite \geq mare basalt $>$ SNC \gg terrestrial basalt, as V content increases (Table 2). This is the same order in which Cr/Mg values decrease (Table 2).

Data for V show, once again, that there is an overall compositional similarity between mare basalts and eucrites. The near-chondritic Cr/V values in mare basalts and eucrites are plausibly interpreted to indicate that Cr/V values in the Moon and HED asteroid are roughly chondritic. This contrasts with the models of Wänke et al., which imply significantly nonchondritic Cr/V values in the Moon and HED asteroid (Fig. 1). The data imply that basalt formation in the Moon and HED parent body involved only a minor fractionation of Cr from V, in contrast to the situation for the Earth. For the Earth, whatever phase or phases fractionated to produce Cr depletions in terrestrial magmas evidently lacked significant V, because V contents in the basalts are not low. If differences in fO_2 were responsible for the systematic differences in Cr abundance between the different planetary objects (Papike and Bence, 1978; Basaltic Volcanism Study Project, 1981), there is little evidence that such differences in fO_2 affected the partitioning of vanadium.

3.4.3. Manganese

Fig. 12 shows the relationship between MnO abundance, FeO/MnO ratio, and La abundance for chondrites, shergottites, terrestrial basalts, mare basalts, and eucrites. The FeO/MnO

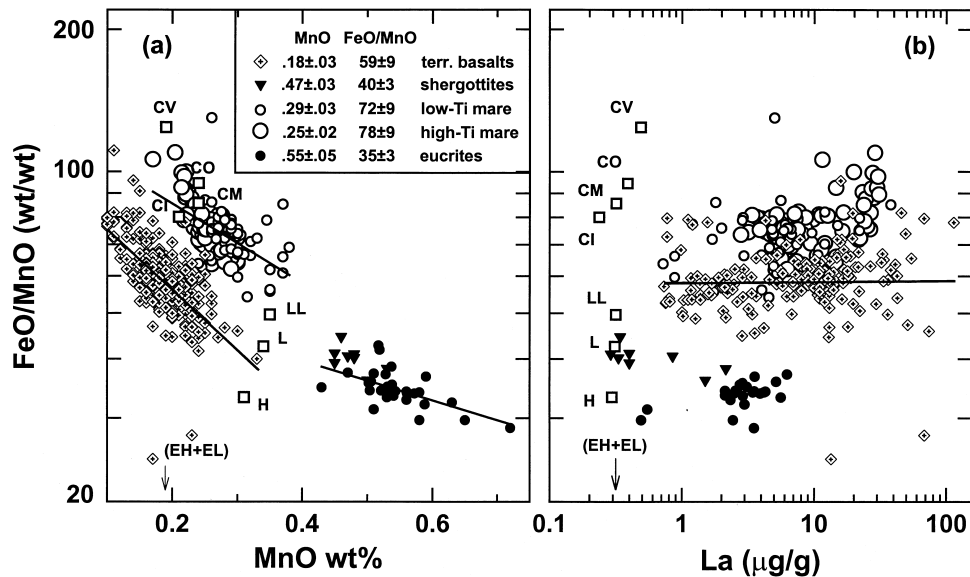


Fig. 12. FeO/MnO abundance ratio plotted against (a) MnO and (b) La abundances for samples in the planetary basalt suite and chondrites. Regression lines are shown in (a) for terrestrial basalts, mare basalts, and eucrites, and in (b) for terrestrial rocks only. Square symbols indicate chondrites. Data sources are given in the Appendix.

ratio is not significantly affected by magmatic processes (e.g., Laul et al., 1972; Dreibus et al., 1977), and in terrestrial basalts, this ratio is relatively constant despite a two-order-of-magnitude variation in La abundance (Fig. 12b). The abundances of MnO and FeO are also relatively constant (Table 2). However, there appears to be a negative correlation between FeO/MnO values and MnO abundances for terrestrial basalts, mare basalts, eucrites, and possibly shergottites (Fig. 12a).

The low MnO abundances of mare basalts and terrestrial basalts compared to shergottites and eucrites (Table 1) have been taken by some as evidence of a genetic link between the Moon and Earth (e.g., Dreibus and Wänke, 1979, 1980; Wänke and Dreibus, 1986; Ringwood et al., 1991). However, lunar and terrestrial basalts themselves differ in MnO abundances and FeO/MnO ratios, as was previously recognized (Dreibus et al., 1977; Drake, 1986). When FeO/MnO ratios and MnO abundances are considered together, lunar and terrestrial basalts clearly have nonoverlapping compositions (Fig. 12a). Indeed, in terms of FeO/MnO ratios and MnO content, lunar and terrestrial basalts differ as much or more from each other than eucrites differ from shergottites (Fig. 12a). Considering FeO (total iron) abundances, terrestrial basalts appear unlike all other terrestrial basalts (Table 1). Thus, each of the basalt suites is characterized by a different FeO/MnO ratio and by MnO and FeO abundances (Fig. 12 and Tables 1 and 2), and this weakens the case for a genetic link between the Earth and Moon.

The apparent inverse correlations between MnO abundance and FeO/MnO ratio (Fig. 12a) are striking. If these correlations were produced by magmatic fractionation, one would expect the FeO/MnO value or MnO abundance to correlate with La abundance, but this is not observed (Fig. 12b). Instead, it is suggested that the measured abundance of MnO varies slightly as a result of analytical imprecision, and that this results in the inverse trends in Figure 12a. As support for this, when different basalt suites are compared, the average rate of change of

FeO/MnO values appears to be correlated with the average MnO content (Fig. 12a). This is the pattern expected for analytical imprecision in MnO determination. Thus, the inverse trends shown in Figure 12a may not be significant. Nonetheless, Figure 12 demonstrates a clear compositional distinction between lunar and terrestrial basalts.

Different average FeO/MnO abundance ratios between the basalt suites (Table 2) probably reflect, at least in part, the accretion of materials with different average oxidation states and FeO/MnO ratios. A protolith similar to H-chondrites has been suggested for the HED asteroid based on FeO/MnO ratio (Dreibus and Wänke, 1980). A protolith similar to CI-chondrites has been suggested for the Moon based on geophysical and geochemical models (Jones and Hood, 1990), and such a precursor is consistent with the high FeO/MnO values of mare basalts (Fig. 12). Similarly, material accreting to the Earth and Mars could have had average oxidation states and FeO/MnO values similar to an LL-chondrite and L-chondrite, respectively, based on the FeO/MnO values in terrestrial basalts and shergottites.

Eucrites and shergottites have MnO abundances that are higher than those of chondrites, whereas mare and terrestrial basalts have progressively lower MnO abundances, generally similar to those in chondrites (Fig. 12a). This difference has been attributed to the segregation of Mn into the Earth's core and the derivation of the Moon from the Earth's mantle (e.g., Dreibus and Wänke, 1979, 1980; Ringwood, 1986; Ringwood et al., 1991; Wänke and Dreibus, 1986). However, the basalt data can be explained if Mn behaved as an incompatible element during the formation of eucrites and shergottites, and largely as an "indifferent" (neither compatible or incompatible) element during the formation of mare basalts and terrestrial basalts. Mineral-melt partition coefficients (D -values) for Mn vary in basaltic systems depending on fO_2 (Drake et al., 1989), and vary in pyroxene and olivine from less than to greater than

unity, depending on temperature and Si/O value in the magma (Irving, 1978). This means that the partitioning behavior of Mn can vary from moderately incompatible to moderately compatible, and basalts with MnO abundances somewhat greater or less than the starting values (assumed to be chondritic) can result. Thus, the lower MnO abundances in terrestrial and mare basalts should not necessarily be taken to imply a special, genetic link between the Moon and Earth.

4. CONCLUSIONS AND IMPLICATIONS

A straightforward interpretation of key geochemical data for basaltic rocks on four different planetary bodies (the Moon, Earth, HED parent body, and SNC parent body) leads to the following conclusions. (1) Basalt source regions in all four of the planetary bodies are generally depleted in volatile alkali elements relative to chondrites, with depletions increasing in the sequence: SNC ~ Earth < Moon ~ HED. The Moon and HED asteroid clearly experienced similar, high-temperature fractionations. (2) Lunar and eucrite basalts, and to a lesser extent shergottites and terrestrial basalts, have low abundances of various trace siderophile elements (Ni, Co, Ga, Ge, Re, and Ir), as a result of metal-alloy fractionation. Nickel, Co, Ga, and Ge abundance systematics imply that metal was segregated from the source regions in the planetary bodies early, before basalt formation. This metal segregation probably corresponds to core formation. (3) Contrary to previous assertions, a good case can be made that the Moon and HED asteroid had similar initial abundances of elements such as Ni, Co, Cr, V, Mg, and Fe. During basalt formation, these elements were fractionated by the separation of ferromagnesian minerals (olivine and pyroxene) in such a way so as to produce overlapping compositions between high-Ti mare basalts and eucrites. (4) There are no significant compositional similarities between basalt source regions in the Moon and Earth, although Mn abundances were only slightly different. This does not support the direct derivation of the Moon from the Earth's mantle. (5) Together with evidence that the Moon and HED asteroid did not form in the same event or place (see below), it follows that some important compositional features of the Moon (volatile-element, siderophile-element, and ferromagnesian-element abundances) were not necessarily established by unique processes operating in a geocentric environment.

Both the Moon and HED asteroid experienced early differentiation, core formation, and early volatile-element loss (e.g., fractionation of Rb from Sr), close to 4.56 Ga ago (Taylor, 1986; Taylor and Norman, 1990; Taylor and Esat, 1996). There is no evidence that they were affected by Raleigh-type distillation of volatile elements, as might be expected for high-temperature vaporization processes (Newsom and Taylor, 1989; Taylor and Esat, 1996). The low overall density of the Moon ($3.344 \pm 0.002 \text{ g/cm}^3$) implies that it has a low metal content (Wood, 1986). Asteroid 4-Vesta is probably the HED parent body (Gaffey et al., 1989). The density of Vesta ($3.54 \pm 0.42 \text{ g/cm}^3$) overlaps that of the Moon, and allows for a low metal content in Vesta as well (Ruzicka et al., 1997).

The many geochemical similarities between the Moon and HED asteroid imply that they had similar origins. Yet the two objects appear to have formed in different nebular environments and times. Oxygen-isotopic (Clayton and Mayeda, 1975)

and Cr-isotopic compositions (Lugmair and Shukolyukov, 1998) of lunar, terrestrial, and meteorite samples imply that the Moon formed proximal to the Earth, close to or less than 1 A.U. from the sun (Wood, 1986; Taylor and Norman, 1990; Taylor and Esat, 1996), whereas the HED body formed elsewhere, possibly in the asteroid belt. The Moon and HED body formed at slightly different times, based on W-isotope data (Lee and Halliday, 1997; Lee et al., 1997; Halliday and Lee, 1999). Altogether, the data imply that the Moon and HED parent body formed in different events, and that at least one of these events occurred outside the geocentric environment.

Which hypothesis best accounts for the origin of the Moon? None of them can be firmly excluded, but some seem more likely than others. Hypotheses that involve formation of lunar material from the Earth (rotational fission; small-impact collisional ejection) seem unlikely. First, isotopic constraints preclude producing the HED asteroid from terrestrial material, so any model that relies on producing a lunar- or HED-like composition from the Earth is faced with the fact that this is seemingly unnecessary. Second, the composition of the Moon is not especially similar to that of the Earth's mantle, so there is no reason to believe that material simply was transferred from the Earth to the Moon.

The capture hypothesis envisions capture into Earth orbit of a lunar-sized object that was originally in heliocentric orbit. The object is either captured intact or disrupted and reaccreted following a close approach to the Earth. Support for this hypothesis follows logically from the conclusion that the Moon and Earth have different compositions, and that the Moon and HED asteroid have similar compositions. However, capture is dynamically difficult to accomplish (Wood, 1986; Boss and Peale, 1986), although not impossible (Singer, 1986). It is also unclear whether the capture process would, by itself, result in volatile depletion or metal loss.

The most popular model of lunar origin, giant-impact collisional ejection, removes material both from the Earth and the impactor to create the Moon. If most of the lunar material originated in the Earth, this model would suffer from the same problems identified above for rotational fission and small-impact collisional ejection. If, instead, the Moon is largely derived from the impactor, and if such an impactor already had the compositional attributes of an HED-like body, this would be more consistent with the data. In this case, the giant-impact process is needed primarily to put material into lunar orbit, not to affect chemical changes. Taylor and colleagues (Taylor, 1986; Taylor and Norman, 1990; Taylor and Esat, 1996) suggested that the inner solar system could have been populated by many volatile-poor planetesimals similar in composition to the Moon and Vesta. Volatile-loss in such planetesimals would have occurred as a result of still poorly understood nebular processes before the giant impact (Taylor and Norman, 1990; Taylor and Esat, 1996). In these models, one such object could have collided with the Earth to form the Moon; another could have been incorporated in the asteroid belt to form Vesta. Metal-loss for the proto-Moon presumably would have occurred mainly as a result of the giant impact. This variant of the giant-impact process predicts that the metal content of Vesta could be much higher than that of the Moon, because the giant impact that facilitates metal loss affects only the Moon, and not Vesta.

The co-accretion or “double planet” hypothesis calls for the Moon to form out of material in orbit around the Earth, most likely present originally in the form of a circumterrestrial disk. Material in the disk could have been supplied by impacts on the Earth (a variant of the small-impact or giant-impact hypotheses), or by material in heliocentric orbit that was subsequently captured (a variant of the capture hypothesis). Disks supplied by impacts on the Earth entail the same problems identified above for the small-impact-collisional-ejection and fission models. Disks formed by supply from heliocentric orbit appear to be more consistent with the data. Such disks are capable of resulting in metal-silicate fractionation, by allowing selective capture of the fragmented silicate mantles of differentiated planetesimals (Weidenschilling et al., 1986). If many heliocentric planetesimals were volatile-depleted (Taylor and Norman, 1990), a proto-lunar object that was both metal- and volatile-depleted could have been produced in Earth orbit. Such volatile-depleted heliocentric objects could have also accreted to form Vesta, but Vesta would not necessarily be metal depleted unless it, too, formed in a protoplanetary disk.

To summarize, the rotational fission and small-impact collisional ejection hypotheses of lunar origin seem unlikely. The co-accretion and capture hypotheses seem tenable, as does a “giant impact” event in which the composition of the Moon is inherited largely from the impactor.

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APPENDIX**References for Database**

- Mare basalts: Papike et al. (1998), supplemented with additional data from the literature
- Eucrite basalts: Kitts and Lodders (1998), supplemented with additional data from the literature.
- SNC meteorites: Lodders (1998)
- Terrestrial mafic and ultramafic rocks:
- Basaltic Volcanism Study Project (1981)
 - Brügmann et al. (1987, 1993);
 - Devey et al. (1994)
 - Halliday et al. (1995)
- Hertogen et al. (1980)
- Jochum et al. (1991)
- Kent et al. (1997)
- Laul et al. (1972b)
- Marsh et al. (1998)
- McGoldrick et al. (1979)
- Neal et al. (1997)
- Newsom et al. (1986)
- Peate (1997)
- Perfit et al. (1996)
- Rehkämper et al. (1999)
- Smith et al. (1994)
- Chondrites: Wasson and Kallemeyn (1988); Jarosewich (1990)