The Bulk Composition of the Eucrite Parent Asteroid and its Bearing on Planetary Evolution

Gerlind Dreibus and Heinrich Wänke
Max-Planck-Institut für Chemie (Otto-Hahn-Institut), Mainz, Germany

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Dedicated to Prof. Dr. Heinrich Hintenberger on the occasion of his 70th birthday

It is shown that howardites fit extraordinary well into a binary mixing diagram for both their major and trace element compositions. Eucrites and diogenites would be suitable endmembers. In the mixing diagram computed from the elemental compositions of howardites, we find at a certain position a composition with very special features. This composition designated PR* contains all refractory incompatible elements in almost C 1, i.e. primitive, abundances. If 43% olivine is added to PR* in order to match the C 1 value for the Mg/Si ratio, a composition is obtained which has almost exact C 1 abundance values for all lithophile elements of non-volatile character. Because of its probable genetic relation we have used an olivine composition equal to that of pallasites. An eucrite parent body (EPB) with eucrites, diogenites and pallasites as the major building blocks has been previously suggested by various authors.

The bulk composition of the EPB, resulting from our computations is found to be almost chondritic, but with a considerable depletion of volatile and moderately volatile elements. A comparison of the bulk composition of the EPB with that of Earth and Moon reveals a number of remarkable differences. Thus, the similarity of the composition of the silicate phases of Earth and Moon becomes even more remarkable and must be taken as strong indication for the genetic relationship of Earth and Moon.

1. Introduction

The parent body of eucrites (i. e. basaltic achondrites, a rare class of differentiated meteorites) is besides Earth and Moon the third planetary object from which we have basaltic rocks for laboratory investigations. The unique shape of the reflectance spectrum obtained for asteroid number 4, Vesta, is very similar to what one finds in laboratory experiments for the basaltic achondrites [1, 2]. So far, Vesta seems to be the only asteroid with such a surface composition. Of course, there could be smaller asteroids with similar reflectance spectra. In any case, Vesta having a radius of about 270 km represents the largest possible eucrite parent body (EPB). Basalt genesis on such a small object with its low gravity is of special interest. Inside the Earth we have to deal with pressures up to megabars compared to only kilobars in the case of Vesta. In addition, the bulk chemical composition of such a small object yields important constraints on the processes which lead to the formation of planets.

In an earlier paper [3] on the composition of the EPB, we have used an evolutionary model, very similar to that outlined by Mason [4]. Since the variations of the compositions of howardites are sufficiently large, we were able to set up a mixing diagram with howardites alone without making any assumptions of the endmembers. Eucrites and diogenites would compositionally be suitable endmembers. Jérome and Goles [5] and McCarthy et al. [6] have previously proposed that howardites are mechanical mixtures of eucrites and diogenites.

In the meantime more analytical data on the chemistry of howardites have been obtained by our group as well as by other authors, including a great number of data on trace elements. In the following we will report on a second iteration of our mixing computation. Furthermore, a better defined olivine phase will be used in order to improve the estimation of the bulk chemistry of the EPB.

2. Mixing Computation

The data used for the computation of our mixing diagram are listed in Table 1. In addition to the major elements Si, Al, Ca, Mg, and Fe, the compatible trace element Sc was used to set up the mixing diagram given in Figure 1. As in the previous paper [3], we only assume that the howardites are two component mixtures at least for the six elements in question. Both the element lines as well as the

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Table 1. Results (weight fractions) of the mixing computation. M = concentrations measured in howardites. C = concentrations calculated. All analytical data from this laboratory [7—10], except those for Zmenj, which are taken from McCarthy et al. [6].

		Malvern	Molteno	Le Teilleul	Kapoeta	Zmenj	Yamato 1	Frankfort
Si	M	23.0	24.1	23.7	22.9	23.4	23.8	23.8
%	C	23.3	23.4	23.5	23.5	23.6	23.7	23.7
Mg	M	7.26	8.63	9.41	9.50	10.41	12.89	12.63
%	C	7.33	8.51	9.46	9.70	10.53	12.58	12.75
Al	M	5.24	4.86	4.15	4.38	3.43	2.26	2.26
%	C	5.40	4.72	4.17	4.03	3.55	2.37	2.27
Ca	M	5.80	4.95	4.42	3.93	3.89	2.74	2.30
%	C	5.63	4.94	4.38	4.24	3.75	2.56	2.46
Fe	M	14.15	13.94	13.80	13.60	13.39	12.99	14.11
%	C	13.99	13.87	13.78	13.75	13.67	13.46	13.45
Sc	M	26.5	24.9	23.4	22.2	—	18.1	20.5
ppm	C	26.1	24.6	23.3	23.0	22.0	19.3	19.1
Li	M	6.50	6.00	5.00	4.80	—	3.40	3.35
ppm	C	6.44	5.75	5.19	5.05	4.56	3.36	3.26
F	M	15.0	11.0	12.0	13.0	—	6.00	—
ppm	C	14.8	13.0	11.5	11.1	9.81	6.62	6.35
Na	M	2730	2310	1800	2270	—	930	1010
ppm	C	2731	2347	2036	1958	1685	1017	962
P	M	305	—	180	—	200	—	150
ppm	C	281	249	224	217	195	140	136
Ti	M	2700	—	2100	2200	1920	1400	1360
ppm	C	2703	2412	2177	2118	1912	1406	1365
V	M	91.4	98.9	—	—	—	124	—
ppm	C	91.5	98.7	105	106	111	124	125
Cr	M	3855	4600	5950	5050	5500	6970	7940
ppm	C	3848	4627	5256	5414	5967	7320	7432
Mn	M	4060	4030	4200	4240	4050	4050	4340
ppm	C	4071	4099	4122	4128	4149	4198	4202
Ga	M	1.27	—	0.82	1.04	—	0.51	0.51
ppm	C	1.25	1.09	0.96	0.92	0.81	0.52	0.50
Sr	M	59	76	41	—	—	22	24
ppm	C	68	58	50	48	41	24	22
Zr	M	38.0	—	26.0	—	—	9.0	14.0
ppm	C	37.3	31.6	27.0	25.8	21.7	11.8	11.0
Ba	M	—	—	14.6	—	—	8.3	7.9
ppm	C	19.0	16.6	14.6	14.1	12.4	8.3	7.9
La	M	2.27	2.29	1.41	1.53	—	0.68	0.98
ppm	C	2.29	1.96	1.69	1.63	1.39	0.81	0.77
Sm	M	1.28	1.14	0.85	0.90	—	0.42	0.56
ppm	C	1.26	1.08	0.95	0.91	0.79	0.49	0.46
Eu	M	0.45	—	0.32	0.33	—	0.17	0.18
ppm	C	0.44	0.38	0.34	0.32	0.28	0.18	0.17
Yb	M	1.35	1.42	1.00	0.94	—	0.50	0.62
ppm	C	1.41	1.22	1.07	1.03	0.89	0.56	0.54
Hf	M	0.90	—	0.65	0.65	—	0.33	0.49
ppm	C	0.87	0.77	0.68	0.66	0.59	0.41	0.39
Ta	M	110	—	80	—	—	42	35
ppb	C	110	94	81	78	67	39	37
W	M	—	—	37	36	—	16	—
ppb	C	52	44	37	36	30	16	15
U	M	—	—	46	51	—	22	38
ppb	C	61	54	49	48	43	31	30

sample locations were computed by a least squares fit method. The compositions obtained from binary mixing computations and the analytically determined compositions are compared in Table 1. In most cases the deviation between calculated values and the observed concentrations stays within the range of the analytical uncertainties.

In the mixing computation (Fig. 1 and Table 1) all howardites have been included, for which both the major element composition as well as data on a

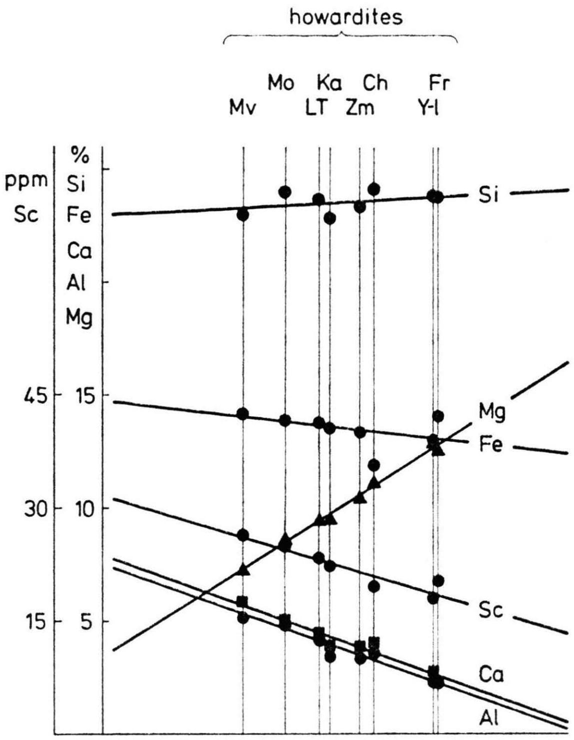

Fig. 1. Mixing diagram computed from the compositions of howardites, assuming that they are mixtures of two components. Data used are listed in Table 1. Howardites: Mv = Malvern; Mo = Molteno; LT = Le Teilleul; Ka = Kapoeta; Zm = Zmenj; Ch = Chaves; Y-l = Yamato l; Fr = Frankfort

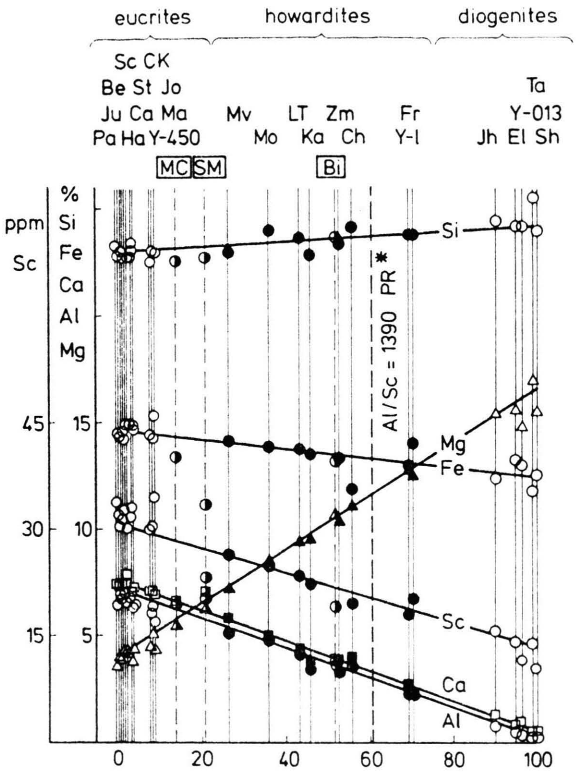

Fig. 2. Without changing the element lines of Fig. 1, the positions of the eucrites and diogenites were calculated by least squares fits. Data used are from McCarthy et al. [6] and from the Mainz laboratory [7—10]. Eucrites: Pa = Pasamonte; Ju = Juvinas; Be = Béréba; Sc = Sioux County; Ha = Haraija, Ca = Cachari; St = Stannern; CK = Chervony Kut; Jo = Jonzac; Ma = Macibini; Y-450 = Yamato 74-450. Diogenites: Jh = Johnstown; El = Ellemeet; Y-013 = Yamato 74-013; Ta = Tatahouine; Sh = Shakla. Anomalous eucrites: MC = Moore County; SM = Serra de Magé; Bi = Binda (half filled circles).

sufficient number of trace elements were available. The only exception was the meteorite Binda, which gave a reasonable fit for the major elements, but showed large deviations for many trace elements. Hence, we have discarded Binda from the mixing computation. However, we will return to this meteorite later on.

From the element lines computed from the compositions of howardites we have calculated the positions of eucrites and diogenites. Figure 2 clearly demonstrates that eucrites and diogenites are suitable endmembers for the howardites. However, the excellent fit to the element lines does not exclude the possibility that howardites are derived from endmembers with a more fractionated composition as long as their composition fits into the mixing diagram. The presence of orthopyroxenes in howardites more Mg-rich than those from diogenites has been emphasized by Takeda et al. [11], who stated that the most Mg-rich orthopyroxenes in howardites may approach that of the mesosiderite Steinbach. Similar observations were made by Reid [12], Bunch [13], Simpson [14], and Dymek et al [15]. Göpel and Wänke [16] also found pyroxenes in the howardite Kapoeta, which are somewhat richer in Mg than those known from diogenites.

3. Bulk Chemistry of the EPB

a) *Major Elements and Scandium*

For a certain binary composition (designated as Pr* in Fig. 2), the mixing diagram yields a composition with unfractionated relative abundances of refractory lithophile elements. Elements such as Al, Ca, Ti, Sc, REE, Sr, Ba, Zr, Hf, etc. with highly different geochemical behaviour occur in about the same ratios as in unfractionated primitive matter (carbonaceous chondrites type 1, C 1). Chondritic abundance ratios of these and other elements at one binary composition cannot be fortuitous [9]. This fact underlines the significance of the composition PR* for the bulk composition of the EPB.

There is considerable evidence that the refractory elements did not fractionate from each other during condensation. In planetary objects they should therefore be present in C 1 abundance ratios [17 – 20]. As noted previously [3], the fact that PR* contains all refractory elements in C 1 abundance ratios indicates that besides eucrites and diogenites no other phases contribute significantly to the abundances of these elements on the EPB. As many of the refractory elements are highly incompatible elements this should also be true for non-refractory incompatible elements like K, Rb, etc.

The Mg/Si ratio of PR* is 0.48, i. e. considerably below the C 1 value of 0.88 [21]. The only major phase which has a higher Mg/Si ratio than C 1, but leaves most of the other element ratios unchanged, is olivine. Only very small amounts of olivine are found in howardites. The calculated normative composition of PR* yields only 3.7% olivine. Obviously, the olivine layers were not involved in the brecciation process which produced the howardites.

From data on chondritic meteorites we know that the Mg/Si ratio is somewhat variable. It is, however, less variable than the Al/Si ratio. Hence, we assume for the moment a C 1 Mg/Si ratio for the bulk composition of the EPB. We, then, calculate that an amount of 43% olivine has to be added to PR* to find the bulk composition of the silicate portion of the EPB.

Previously, we assumed the composition of lunar dunite 72417 being representative for the missing olivine phase, because of the chemical similarity of the outer regions of the moon with that of the EPB [3].

Clayton et al. [22, 23] have shown that the pallasites fall on the oxygen isotope fractionation line of the eucrites and diogenites. This observation as well as others [24, 25] point towards a genetic relation between eucrites, diogenites and pallasites. Therefore, we have now taken the composition of the silicate phase (almost pure olivine) of the pallasite Marjalahti for the calculation of the bulk chemistry of the EPB. Also in our first paper PR* was calculated at the position where the Al/Sc ratio matches that of C 1 chondrites. In contrast to the case of lunar dunite 72417, the Al/Sc ratio of the silicate phase of Marjalahti is very different from the C 1 value. Hence, the computation reported here was carried out in such a way that for the resulting final bulk composition of the EPB both the Al/Sc as well as the Mg/Si ratio match the C 1 values. Because of the low concentrations of both Al and Sc in the silicate phase of Marjalahti [10], their overall contribution is small as can be seen from Table 2, in which we have summarized the final result of these calculations.

Table 2. Calculation of the bulk composition of the silicate portion of the EPB.

	PR*	Olivine	EPB 57%PR* +43% olivine	C 1 (Orgueil) [21]	EPB rel. to Si and C 1
Mg %	11.42	29.0	19.0	9.36	1.0
Al	3.04	0.01	1.73	0.82	1.04
Si	23.62	18.9	21.59	10.68	1.0
Ca	3.23	–	1.84	0.90	1.01
Ti	0.169	–	0.096	0.044	1.08
Fe (FeO)	13.58	8.75	11.50	18.26	–
Li ppm	4.04	0.83	2.7	1.45	0.92
F	8.4	–	4.8	54	0.044
Na	1395	86	830	5017	0.08
P	171	–	97	1010	0.048
Cl[a]	8	–	4.6	678	0.003
K[a]	134	–	76	517	0.07
Sc	20.8	1.46	12.4	5.9	1.04
V	117	56	91	55.6	0.81
Cr	6550	5220	5980	2670	1.11
Mn	4170	2120	3290	1820	0.89
Co[a]	17	7	13	501	0.013
Ni[a]	40	34	38	10770	0.002
Ga	0.68	0.66	0.67	9.1	0.036
Br[a]	0.054	–	0.03	2.53	0.006
Sr	33.5	–	19.1	8.6	1.10
Zr	17.4	–	9.9	3.82	1.28
Ba	10.6	–	6.0	2.2	1.35
La	1.14	–	0.65	0.245	1.31
Sm	0.66	–	0.38	0.154	1.22
Eu	0.24	–	0.14	0.058	1.19
Yb	0.75	–	0.43	0.165	1.29
Hf	0.51	–	0.29	0.12	1.20
Ta	0.055	–	0.031	0.017	0.90
W	0.024	–	0.014	0.089	0.078
U	0.038	–	0.022	0.0082	1.33

[a] Calculated from indigenous concentrations. Dashed lines in Figs. 4b, 10a, b, and 11a, b, c.

b) Trace Elements

In addition to the major elements and Sc, Table 2 also contains data on a large number of trace elements. Their abundances were obtained in the following way.

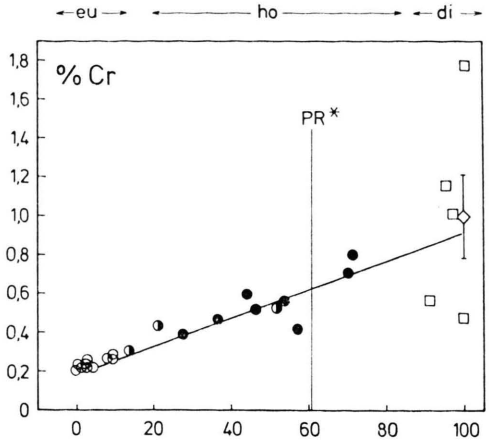

Fig. 3. Mixing line for Cr. Open symbol with error bars corresponds to the mean value of Cr concentrations measured in the five diogenites. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

Using the howardite positions obtained from the mixing diagram of Fig. 1, we have constructed mixing diagrams for a great number of trace elements. Again the element lines were calculated from least squares fits of the elemental abundances of the howardites alone except for some special cases which we will discuss below. The data points for the eucrites and diogenites should only illustrate the validity of the mixing model.

The excellent fit for compatible trace elements Sc and Cr (Figs. 2 and 3) is no surprise, knowing the results for the major elements. The superiority of our approach – not to use the endmembers, but the mixtures for the construction of the mixing diagrams – becomes especially clear for chromium. Diogenites are rare meteorites. We have reliable data only for five of them. As seen from Fig. 3, the Cr contents of these five diogenites scatter considerably. Since there is no well defined Cr content of diogenites, it would be hard to choose the right Cr value for an assumed diogenitic endmember. In fact, it is merely by accident that mean value (open symbol with error bars in Fig. 3) falls so close to the element line based on the howardite compositions. Obviously chromite is very inhomogeneously distributed within diogenites and the diogenitic component in howardites must represent a good average of the orthopyroxene layer of the EPB.

In the case of V, the situation is very similar (no figure was included for V to save space). It is important to note that the Mg-rich (right hand side, Fig. 3) endmember is the major contributor for Cr and V, contrary to the situation for most other trace elements, except also Ni and Co.

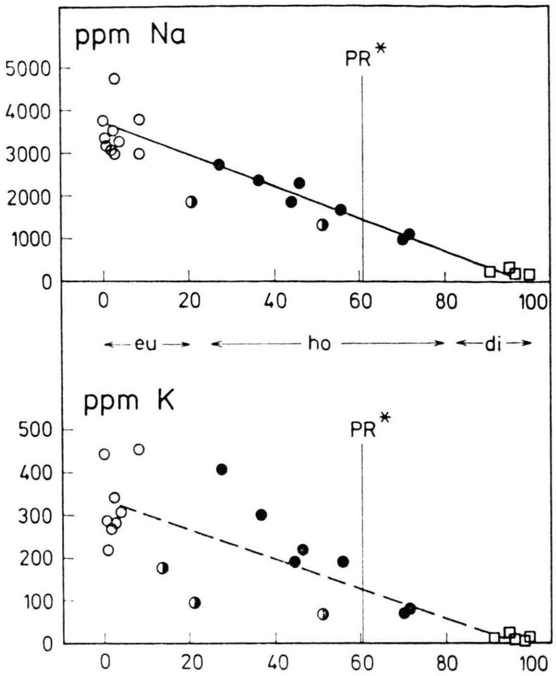

Fig. 4a and b. Mixing line for Na. The dashed line in the lower part of the figure connects the mean values of the K concentrations, measured in eucrites and diogenites. See text for explanation. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

A good fit is also found for Na and Ga (Figures 4 a and 5 a). As one would expect, the data points from eucrites scatter more and more according to the increasing incompatible character of the elements considered. Europium, which due to the low oxygen fugacity [26, 27] of eucrites is mainly present in the 2^+ state, shows little scatter and a still excellent fit is obtained (Figure 6 a). The scatter becomes larger for Yb (Fig. 6 b), Ti and Zr (Figs. 7 a, b) and is, of course, largest for highly incompatible elements like Sm, La (Figs. 8 a, b) and all other light rare earth elements as well as for F (Figure 5 b). Similar large scatterings were also observed for the elements Hf, Ta, and U (no figures included). Nevertheless, it is interesting to note how well the element lines cut through the field of the eucrite data points.

Tungsten and P (Figs, 9 a, b) are special cases in the sense that both elements behave like incompatible elements in magmatic processes. However,

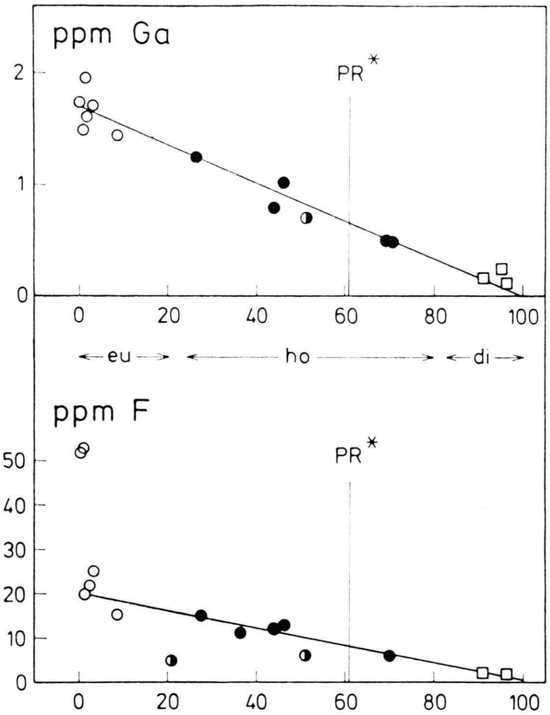

Fig. 5a and b. Mixing lines for Ga and F. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

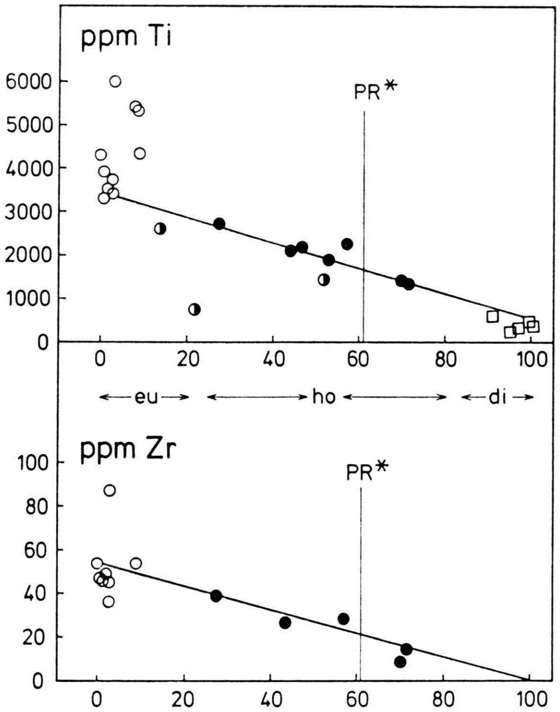

Fig. 7a and b. Mixing lines for Ti and Zr. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

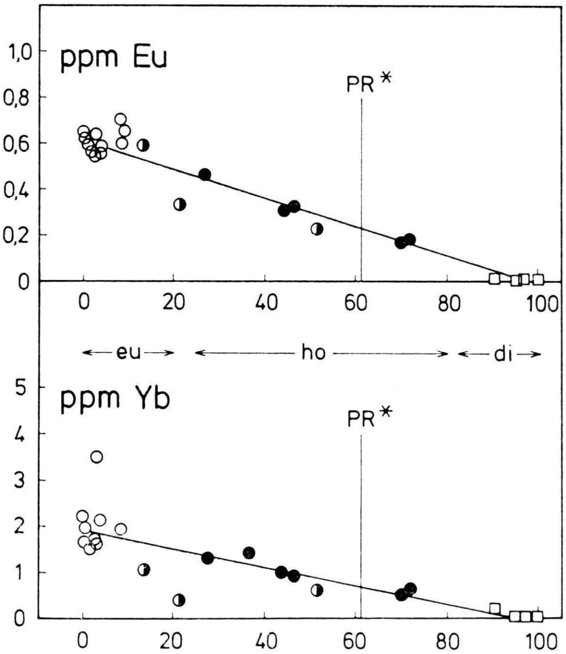

Fig. 6a and b. Mixing lines for Eu and Yb. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

because of their considerably siderophile character they are markedly depleted in the silicate portion of Earth, Moon and also EPB [28]. While W is like the other highly incompatible elements almost absent in diogenites, P is found in diogenites in significant, although highly variable concentrations. As indicated by the element line based on howardites, the Mg-rich component of the howardites must contain appreciable amounts of P, too (Figure 9 b).

For the elements K, Cl, Br, Zn, Ni, and Co element lines cannot reasonably be drawn using the concentrations observed in howardites. Different reasons are responsible for this observation.

Potassium is of highly incompatible character and is furthermore moderately volatile. Hence, large fractionations for this element are to be expected. In the case of siderophile elements like Ni and Co as well as of highly volatile elements like Cl, Br, and perhaps also Zn, the howardites are not pure two component mixtures. For these elements at least one additional component is of importance. Chou et al. [29] attribute the excess of siderophile elements to the admixture of a chondritic component, compositionally similar to CM-chondrites.

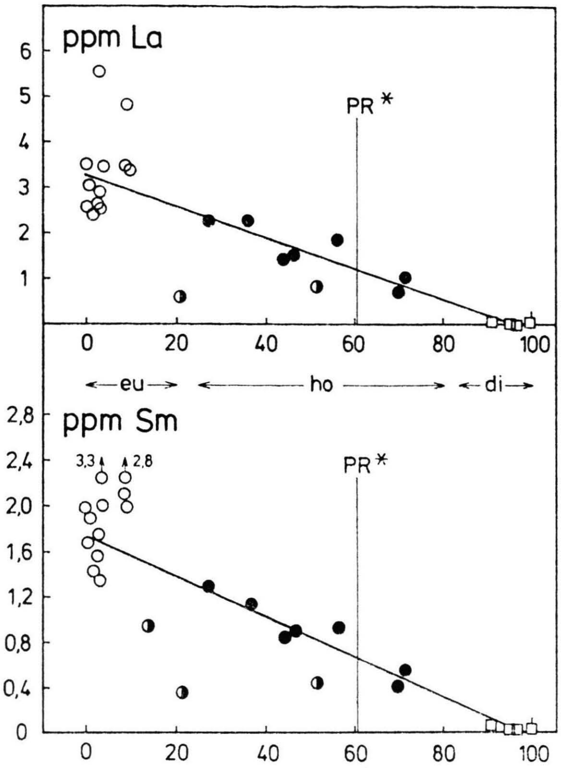

Fig. 8a and b. Mixing lines for La and Sm. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

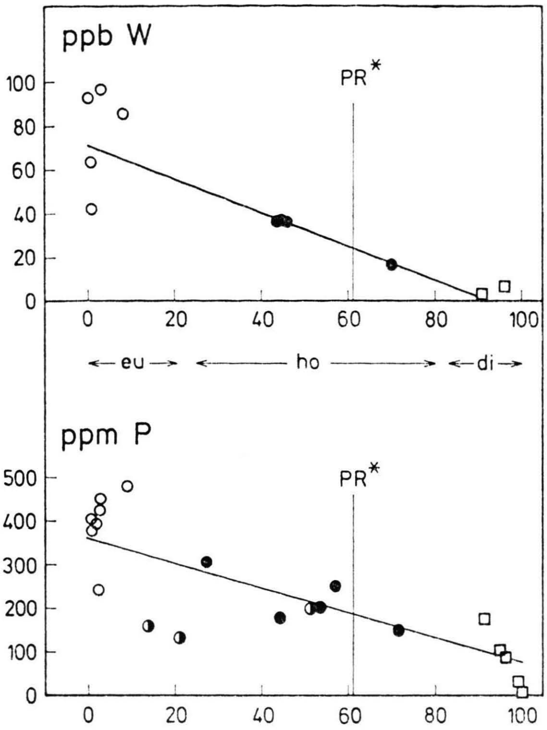

Fig. 9a and b. Mixing lines for W and P. Half filled circles correspond to anomalous eucrites. For references of data used, see caption Figure 2.

For all these elements, instead of constructing the element lines from the data points of howardite mixtures, the dashed lines in Figs. 4 b, 10 a, b, and 11 a, b, c were drawn through the mean values of the concentrations observed for eucrites and diogenites, respectively.

The figures clearly demonstrate abundances in excess of the indigenous concentrations. The presence of solar wind derived rare gases in a number of howardites tells us that howardites are regolith breccias and, hence, the infall of chondritic material seems almost unavoidable. The similarity to the lunar regolith is obvious.

Halogen data on howardites from literature show considerable variations. We have found similar variations in our recent study, the result of which is summarized in Table 3. We have discarded all data given in parentheses as we suspect contamination, especially in the case of chlorine. However, the high Br value for Malvern and to lesser extent that of Kapoeta cannot easily be explained by contamination. Hence, excess amounts up to 100 ppb Br seem to be common in howardites. CM-chondrites contain 600 to 900 ppb Br, while C 1 or C I chondrites contain about 3 ppm Br.

For siderophile elements Chou et al. [29] found excess amounts corresponding to the admixture of about 3% CM-material. Consequently, the presence of excess Br in howardites would require the addition of about 3% of a C 1 component.

Extremely high halogen concentrations accompanied by other volatiles were also found in some of the lunar highland breccias [28]. They are commonly thought to result from exhalations from the lunar interior. Similar processes may well be responsible for part of the excess of Br and other volatiles in howardites, too. Hence, it could be that the high Cl and Br data observed in howardites may in part be real and not due to contamination.

Recently, we have also tried to examine the halogen content of the silicate phase of pallasites. We found unexpectedly high, but variable concentrations. In a sample of Krasnojarsk we measured 410 ppm Cl and 102 ppb Br. After handpicking, we found for clean grains without any sign of alteration

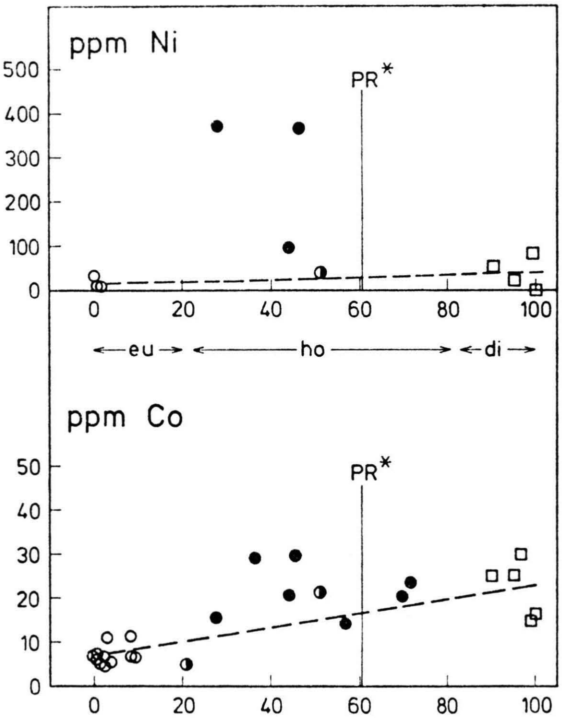

Fig. 10a and b. In the case of Ni and Co, the admixture of a third component (chondritic component) is clearly visible. The dashed line connects the mean value of the Ni and Co concentrations measured in eucrites and diogenites, i.e. it corresponds to the indigenous Ni and Co concentrations expected in howardites. Half filled circles correspond to anomalous eucrites. For references of data used, see caption of Fig. 2 and [29].

Table 3. Chlorine and Br concentrations in howardites.

	Cl (ppm)		Br (ppb)		Cl/Br
	Mainz data [9, 10]	Lit. data	Mainz data [9, 10]	Lit. data	
Malvern	16		172		93
Molteno	(125)		(240)	84 [30]	520
Le Teilleul	(63)		(262)		240
Kapoeta	(147)		170	40, 139 [30] 390 [31]	860
Yamato 1	7.5		74		100
Frankfort T	16	15 [32]	100	66 [30] 360 [32]	160

15 ppm F, 17 ppm Cl, and 30 ppb Br. Since the original sample also had 0.29% H_2O, contamination by serpentinisation is obvious. Not having reliable data we have assumed for the estimation of the bulk composition of EPB the olivine phase to have zero concentrations of F, Cl, and Br.

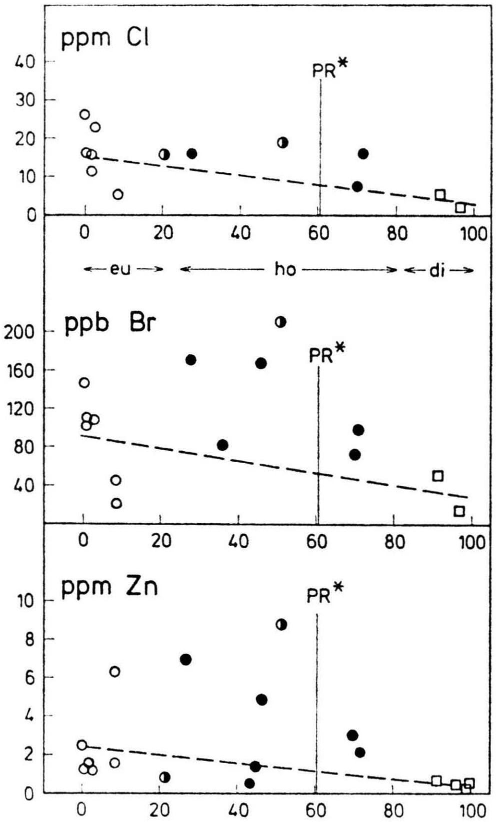

Fig. 11a, b and c. As in the case of Ni and Co, howardites clearly show excess concentrations of Cl, Br and Zn. The dashed lines connect the mean concentrations of Cl, Br, and Zn measured in eucrites and diogenites. The excess amounts of these three volatile elements in addition to the meteoritic component may in part be the result of exhalation processes on EPB. See text for further discussion. Half filled circles correspond to anomalous eucrites. Data used from [7–10, 29–32].

4. The Anomalous Eucrites Moore County, Serra de Magé and Binda

Contrary to other eucrites a cumulate origin has been suggested for Moore County [33] and Serra de Magé [34], which was confirmed by the study of Stolper [26], who also proposed a cumulate origin of Binda. According to their major element chemistry, Moore County and Serra de Magé are similar to the more common eucrites. Binda falls compositionally in the field of howardites. In Fig. 2, the data points of these three achondrites (half filled circles) fall very close to the element lines defined by the howardites. However, large deviations are observed for most of the trace elements, especially those with incompatible character. Binda is excep-

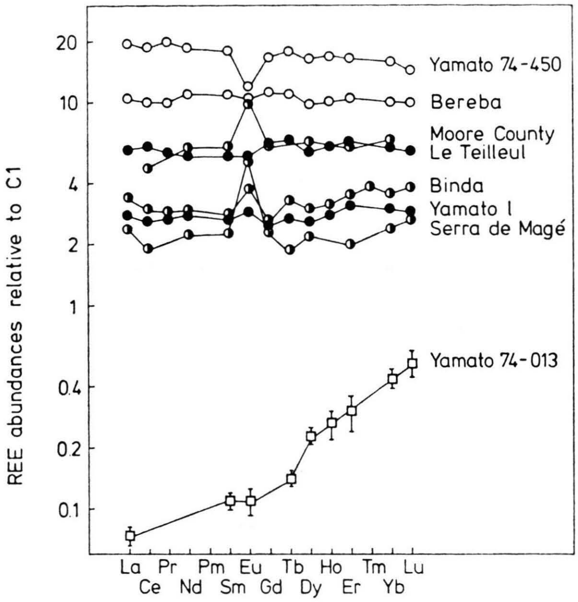

Fig. 12. REE abundances in eucrites, howardites, and diogenites. The positive Eu anomaly observed for the three anomalous eucrites Moore County, Binda, and Serra de Magé is a clear indication of their cumulate origin.

tionally low in all incompatible trace elements. These deviations from the element lines of the mixing diagram in the case of Binda clearly indicate an origin of this meteorite distinctly different from that of all other howardites.

As seen from Fig. 12, Binda, Serra de Magé, and Moore County exhibit a clear positive Eu anomaly, contrary to all other eucrites and howardites which have either flat REE patterns or negative Eu anomalies. The positive Eu anomaly is a further strong evidence for the cumulate origin of Binda, Serra de Magé, and Moore County.

5. Discussion

The major element composition of the EPB as obtained from this work is listed in Table 4 together with the estimates from other authors.

It is obvious that the various estimates for major elements generally do not differ much from each other. This is a striking observation, considering the highly different methods of these estimates. However, all compositions based on the petrology of the EPB as outlined by Stolper [26] give a considerably higher FeO content compared to ours. We have previously argued [3] that FeO concentrations in the order of 27%, which correspond to an abundance value of 0.66 (normalized to Si and C 1) are inconsistent with the low FeO/MnO ratio of 35, observed for eucrites, howardites and diogenites. As the FeO/MnO ratio stays almost unchanged during magmatic processes, the ratio of the bulk composition must be close to 35. The FeO/MnO ratio of carbonaceous chondrites type 1 (C 1) is 100 (taking all Fe as FeO). As loss of Mn due to volatilization would increase the FeO/MnO ratio and not lower it, the C 1 normalized FeO abundance of 0.66 for the EPB would correspond to a FeO/MnO ratio of 66 as a lower limit for the EPB. The only way to lower the FeO/MnO ratio is to assume a FeO content of the EPB considerably below 27%.

Table 4. Chemical composition of the eucrite parent body (EPB) (metal and sulfide free).

%	This work	Vizgirda and Anders [35]	Hertogen et al. [36]	Consolmagno and Drake [37]	Morgan et al. [38]
MgO	31.5	35.0	29.4	29.7	28.5
Al_2O_3	3.27	2.3	2.4	1.8	2.5
SiO_2	46.2	49.3	41.2	39.0	39.8
CaO	2.57	1.9	2.0	1.2	2.06
TiO_2	0.16	0.12	0.12	–	0.13
FeO	14.8	11.0	24.0	28.3	26.6
Na_2O	0.11	0.07	0.05	0.04	0.05
K_2O	0.0092	0.01	0.004	–	0.004
MnO	0.42	0.30	0.46	–	0.018
Cr_2O_3	0.87	–	–	–	–

Bronzite (H-group) chondrites have a FeO/MnO ratio of 32, i. e. very close to that of eucrites. Hence, we conclude that H-group chondrites would provide a suitable source for the silicate phase of the EPB at least for their FeO content. H-group chondrites contain about 18% of metallic NiFe. From the observed W depletion relative to La in lunar rocks, Rammensee and Wänke [39] have estimated an amount of 26% metal in equilibrium with the silicate phase of the Moon. Eucrites have a W/La ratio very similar to that of the Moon. Thus we conclude that the EPB must have had a metal content of at least 20%, again close to the metal content of H-group chondrites.

However, contrary to H-group chondrites which are slightly depleted in refractory elements our estimate yields no depletion for the EPB relative to C 1 abundances (see Table 2, column 6). In fact, we find for Al and Ca abundance values very close to 1. Thus the assumption of the C 1 Mg/Si ratio used for the estimation of the contribution of the olivine phase to the bulk chemistry of EPB has been well substantiated.

Most estimates suggest that the moderately volatile elements Na and K are considerably depleted relative to C 1 abundances. The absolute values vary, however, by about a factor of 2. For Mn the low value given by Morgan et al. [38] is completely unreasonable as it would correspond to a FeO/MnO ratio of 1480.

For all other trace elements no comparison is possible as literature data do not exist. From our data given in Table 2, column 6, we note that the mean abundance of the 10 refractory trace elements is 1.2, i. e. would be slightly higher than that of Al, Ca, and Ti. However, we notice that among the refractory trace elements those with incompatible character are responsible for the higher mean value. Hence, we might suspect an artifact for those elements. The abundances of more compatible trace elements Sc and Sr are within the range of that of Al, Ca, and Ti.

If we compare the bulk chemistry of the EPB with that of the Earth and Moon; we will note a number of interesting similarities as well as striking differences (Table 5). Normalized to Si and C 1, we find no drastic differences in the major element composition. The data for the Earth are estimated from concentrations observed in upper mantle derived rocks [41]. Thus, the FeO value of the Earth could be too low because of an increase of the FeO content in the Earth's mantle with depth. Neglecting FeO, the major element chemistry of the silicate portion of these three objects are identical within a range of 50%, i. e. all three objects have an almost chondritic composition. Moon and Earth are slightly more enriched in refractory elements.

Among the minor and trace elements Na and K are depleted on Earth, Moon and EPB. However, the depletion of Moon and EPB for these elements exceeds that of the Earth by about a factor of 5. To the contrary, Mn seems to be even slightly more depleted on Earth compared to the Moon, but not depleted at all in EPB. Hence, we conclude that volatility is not the reason for depletion of Mn on Earth and Moon.

Table 5. Bulk composition of the silicate portion of EPB, Moon and Earth. Elemental abundances normalized to Si and C 1.

	EPB This work	Moon [8, 40]	Earth [41]
Mg	1.00	1.00	1.25
Al	1.04	1.56	1.30
Si	1.00	1.00	1.00
Ca	1.01	1.57	1.41
Ti	1.08	1.56	1.50
Fe (FeO)	0.31	0.28	0.169
Li	0.92	—	0.72
F	0.044	—	0.153
Na	0.082	0.054	0.244
P	0.048	—	—
Cl	0.0034	—	0.0071 [a]
K	0.073	0.052	0.255
Sc	1.04	1.56	1.46
V	0.81	0.76	0.70
Cr	1.11	0.51	0.60
Mn	0.89	0.38	0.28
Co	0.013	0.079	0.106
Ni	0.0017	0.074	0.099
Ga	0.036	—	0.167
Br	0.0060	—	0.011 [a]
Sr	1.10	1.56	1.65
Zr	1.28	1.56	1.46
Ba	1.35	1.56	1.46
La	1.31	1.56	1.46
Sm	1.22	1.56	1.46
Eu	1.19	1.56	1.46
Yb	1.29	1.56	1.29
Hf	1.20	1.56	1.46
Ta	0.90	1.56	1.46
W	0.078	0.089	0.093
U	1.33	1.56	1.46

[a] In the case of Cl and Br the amounts estimated to be contained in the Earth's crust were added to that observed in the mantle derived rocks [61].

The data for the Moon given by Wänke et al. [8, 40] have been recalculated using for the Mg/Si ratio a value of 0.88 instead of 0.91. This yielded a lower value for the olivine phase (28% instead of 31%).

As it can be seen from Table 5, Cr similar to Mn is depleted on Earth and Moon, but not on EPB. The same behaviour is found for V. The observed concentrations in the Ca, Al-rich inclusions of the Allende meteorite (high temperature condensates [42 – 44]), indicate the refractory tendency of V [14]. As Earth and Moon seem to be slightly enriched in refractory elements, relative to the other refractory elements, the depletion of V for Earth and Moon is even more pronounced (Figure 13).

Let us now investigate the possible reasons which could account for the depletion of Mn, Cr, and V in the Earth's mantle. Ringwood [45] has recently suggested the presence of considerable amounts of FeO dissolved in the Earth's core, due to high pressures and temperatures. One might speculate about a similar behaviour of the oxides of Mn, Cr, and V.

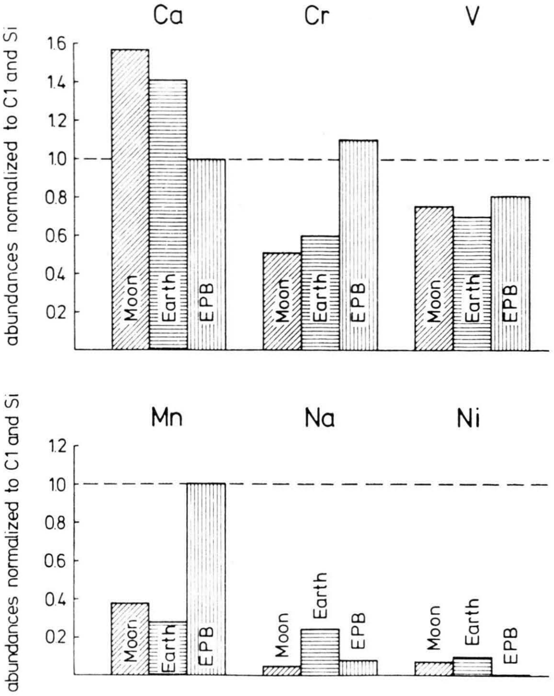

Fig. 13. Comparison of the abundances of Ca, Cr, V, Mn, Na, and Ni in the silicate portion of Earth, Moon, and EPB. Calcium like all other refractory elements is similarly enriched in Earth and Moon, but not on the EPB. Chromium, V, and Mn are depleted to a very similar extent on Earth and Moon, but not on the EPB. The depletion of Na is smaller on the Moon as compared to Earth and EPB. Finally, we note that surprisingly high abundances of Ni are observed for the silicate portion of Earth and Moon, but not for the EPB.

Because of the small mass of the EPB, such an effect is not to be expected in this case.

Another and perhaps more likely reason for the depletion of Mn, Cr and V in the Earth's mantle would be the solubility of their sulfides in the Earth's core. Keil [46] has pointed out that in the highly reduced enstatite chondrites, Mn is concentrated in various sulfide minerals. Chromium and V are also present in enstatite chondrites as sulfides. Thus, if the Earth accreted heterogeneously and its core was formed from highly reduced material a considerable portion of Mn, Cr, and V could be expected to have entered the Earth's core in form of their sulfides. It appears that such a process took place on the parent body of the enstatite achondrites. These meteorites which are thought to have been derived from enstatite chondrites by segregation of metal and sulfide [47], show low concentrations of Mn and very low concentrations of Cr and V [10]. Condensation of V, Cr, and Mn as metals [48] would have a similar result.

A heterogeneous accretion model of the Earth first suggested by Eucken in 1944 [49] and re-introduced by Turekian and Clark in 1969 [50] seems to substantiate more and more. Recently, Jagoutz et al. [41] have gathered evidence from the chemical data of the Earth's mantle in favour of heterogeneous accretion. Clayton et al. [22] have found that terrestrial samples and enstatite chondrites lie on the same oxygen isotope fractionation line.

Herndon [51] has recently suggested that the solid inner core of the Earth should consist of Ni-silicide instead of Ni-Fe metal. Ni-silicide (perryite) has been observed in enstatite chondrites, too [52, 53]. In this case the light element required to be present in the whole core to reduce its density must be Si, perhaps together with sulfur. The presence of metallic Si in the Earth's core was suggested even more than 20 years ago [54, 55].

In the heterogeneous accretion model discussed here the accumulation of the Earth began with highly reduced material, perhaps similar to that of enstatite chondrites, followed by accumulation of more or even completely oxidized material. Such a scenario is also in line with the new model for the formation of the solar system by Cameron, in which the planets are formed from giant gas-spheres [56]. Cameron's new model is in fact in respect to some of its major conclusions very similar to the much earlier work by Lüst [57].

Independent of the question what element is responsible for lowering the density of the Earth's core (O or Si and S), there is in both cases a plausible explanation to account for the observed depletion of Mn, Cr, and V in the silicate portion of the Earth by assuming the missing fractions to be present in the core. Both of the suggested mechanisms would not work on the EPB. The similar depletion of these elements for Moon and Earth is an additional indication of the genetic relationship of these two objects.

A further important result are the low concentrations of oxidized Ni and Co in the silicate phase of the EPB; compared to the high Ni and Co contents of the Earth's mantle. Delano and Ringwood [58] and Wänke et al. [40, 59] have recently collected evidence for Ni and Co concentrations in the primary matter of the Moon at a level similar to that in the Earth's mantle. However, this point has been heavily disputed by Anders [60]. The low concentrations of

Ni and Co in the EPB are within the range to be expected from partition coefficient data.

Dreibus et al. [61] have already underlined the strikingly similar depletion patterns of a number of volatile and moderately volatile elements (like Na, K, Ga, F, Cl) on Earth and EPB with about three times lower absolute abundances for the EPB compared to the Earth.

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