Core formation in the Earth and Shergottite Parent Body (SPB): Chemical evidence from basalts†

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Abstract—Constraints on processes of core formation in terrestrial planets may be inferred from the abundances of siderophile and chalcophile elements in their mantles. Of particular interest is a comparison of processes of core formation in the Earth and in the Shergottite Parent Body (SPB), a terrestrial planet tentatively inferred to be Mars. To this end, we (i) present new INAA and RNAA analyses of the non-Antarctic SNC meteorites, (ii) infer the composition of the SPB mantle from the compositions of the SNC meteorites, (iii) infer the composition of the Earth's mantle from the compositions of terrestrial basalts, and (iv) deconvolve the effects of volatile depletion, core formation, and mineral/melt fractionation on the abundances of siderophile and chalcophile elements in the SPB and the Earth. Element abundances in the mantles of the SPB and the Earth are estimated from element/element correlations observed among basalt samples. In basalts from the SPB (the SNC meteorites), four groups of covariant elements are observed: highly incompatible, moderately incompatible, indifferent and compatible. From correlations within these groups, the SPB mantle is found to be depleted in volatile elements, and strongly depleted in siderophile and chalcophile elements. For the Earth, the element/element correlation method gives a mantle composition similar to previous estimates. Compared to the Earth, the SPB mantle is richer in moderately siderophile elements (e.g., W, P), consistent with its inferred higher oxidation state. Chalcophile elements in the SPB mantle are more depleted than in the Earth's mantle, particularly when compared to estimates of the original abundances of volatile chalcophile elements in the two planets. In the SPB mantle, the Ni/Co ratio is non-chondritic, in contrast to the chondritic ratio in the Earth's mantle. Abundances of siderophile and chalcophile elements in the SPB mantle may be modelled by equilibrium with solid metal and metallic sulfide liquid, with some metal and sulfide trapped in the mantle (i.e., homogeneous accretion and inefficient core formation). Neither this model nor a heterogeneous accretion model is satisfactory in explaining element abundances in the Earth's mantle, particularly the abundances of Ni, Co, Mo, and W. Nevertheless it appears that core formation in the SPB and the Earth left quite different chemical signatures in their planetary mantles.

INTRODUCTION

THE ABUNDANCES OF siderophile and chalcophile elements in the Earth have been the basis of inspired debate concerning the relative importance of exogenous versus endogenous processes in the early geochemical evolution of the terrestrial planets. The focus of most discussion has been the fact that strongly siderophile (e.g., Re, Ir) and chalcophile (e.g., S, Se) elements are present in the Earth's mantle in approximately chondritic relative abundances within each group of elements. One explanation is that the chondritic relative abundances represent addition of chondritic material to the Earth after complete separation of solid metal and metallic liquid to form the core (e.g., KIMURA et

al., 1974; WÄNKE, 1981; CHOU et al., 1983). An alternative explanation is that the chondritic relative abundances are a natural consequence of inefficient separation of metal from silicate to form a core and mantle, with varying emphasis on the role of trapped metallic phases in the mantle (JONES and DRAKE, 1984; BRETT, 1984).

In essence, the difference between the two models rests on the timing of core formation relative to accretion. Both processes may occur simultaneously (STEVENSON, 1981) but it is not clear which process runs to completion first. As both hypotheses can model elemental abundances in the Earth's mantle equally well (or poorly; JONES and DRAKE, 1986), there is little on Earth to recommend one hypothesis over the other.

Fortunately, nature has provided us with samples of another Earth-like planet, the SNC meteorites. These basaltic achondrites include the shergottites (Shergotty, Zagami, ALHA 77005 and EETA 79001), the nakhlites (Nakhla, Lafayette and Governador Valadares), and Chassigny, all of which appear to be from a single planet (the SPB) compositionally similar to the Earth (STOLPER, 1979). Like Earth basalts, the SNC basalts are rich in volatile elements, have relatively high Fe/Mg ratios, and have strongly fractionated REE patterns. Other evidence links the SNC meteorites to Mars (e.g., BOGARD et al., 1984).

Table 1a. Element Abundances in SNC Meteorites and BCR-1 (ppb except as noted)

Sample Run	Shergotty 77-3	Zagami 77-3	Chassigny 77-4	Nakhla 80-2a	Lafayette 80-2b	BCR-1 77-3	77-4	80-2a	80-2b
Ir	0.0285	0.033	1.85	0.153	0.052	0.0014	0.0088	<0.0015	<0.001
Os	<0.0023	0.119	1.36	0.20	<0.6	<0.0015	<0.003	--	--
Re	0.044	0.035	0.054	0.041	0.028	0.80	0.99	0.885	0.878
Au	5.0	1.76	0.56	0.897	(66.2)	0.953	0.86	1.43	1.3
Pd	1.7	1.79	<0.15	42.	<1.7	<0.3	<0.21	<2.2	<2.5
Ni ppm	55	90	450	72	94	10	--	<36	<14.2
Sb	1.7	5.2	0.87	19	(103)	513	541	530	435
Ge ppm	0.69	0.78	0.011	2.97	2.48	1.28	1.22	1.53	1.39
Se	370	320	36.9	63.6	50	83	76	72.2	71.2
Te	2.5	2.2	50	<4.3	<5.2	5.6	5.1	<4.2	--
Ag	16.9	14.2	2.61	(1380)	--	23.9	24.0	26.4	33.0
Br ppm	1.06	0.79	0.11	4.55	0.17	0.065	0.063	--	--
In	26.5	26.6	3.9	14.6	20.1	86.9	92.4	86	80
Bi	0.7	1.64	0.37	54	5.	45.9	52.7	-44.5	(21?)
Zn ppm	68.3	63.8	69	55	72	131.9	125	133	120
Cd	12.9	(179)	14	115	98	151	-150	148	-144
Tl	12.9	11.7	3.7	3.8	6.81	280	335	313	339
Rb ppm	(9.5)	(9.56)	(1.05)	(5.01)	(3.25)	(50.2)	(72.)	(45.5)	(46.3)
Cs ppm	0.529	0.367	0.037	0.349	0.353	1.00	0.994	0.97	0.86
U	129	93.9	14.9	65	44.2	-1750	-1750	-1750	-1750

INAA and RNAA described in text. Errors (1) are less than half of the least significant digit; upper limits are 2 . Dash signifies that element was not analyzed; equal sign signifies that element in BCR-1 was a primary standard; and parentheses signify that an analysis is suspect. Samples from the British Museum (BM), National Museum of Natural History (NMNH), and Field Museum (Me): Shergotty BM41021; Zagami BM1966,54; Chassigny Me2636; Nakhla NMNH 426 and Lafayette Me2116.

Study of siderophile and chalcophile element abundances in the SPB ought to yield insight into core formation and other processes in the SPB. We report new analyses of some SNC meteorites. Elemental abundances in the Earth and SPB are compared to investigate which (if either) of the above hypotheses (exogenous or endogenous) for planetary assembly and differentiation is correct.

ANALYTICAL METHODS AND RESULTS

Chemical analyses of the SNC meteorites were performed by radiochemical and instrumental neutron activation analyses at the University of Chicago. Meteorite samples were obtained from the Field Museum of Natural History (Chicago) and the British Museum (London). Samples of 100–200 mg mass were sealed in ultrapure silica tubes and irradiated for 10 days at a neutron flux of 2×10^{14} ncm^{-2} sec^{-1} at the NBS reactor, Gaithersburg, Maryland. The SNC samples were irradiated in 3 separate runs. Each run included monitors for all elements (except U) and aliquots of standard rock BCR-1. BCR-1 was used as a monitor for U, and also for Cd and Bi in some cases (see Table 1a).

Analyses for the siderophile and volatile elements of Table 1a were performed by the radiochemical separation method of HERTOGEN et al. (1980), based on the methods of KEAYS et al. (1974), GROS et al. (1976) and HERTOGEN et al. (1977). Shergotty and Zagami were analyzed in the same irradiation as the MORB glasses of HERTOGEN et al. (1980). Initial results for Rb were low, and pointed towards accidental chemical fractionation of Rb from Cs during radiochemical procedures. Rb yields were redetermined, but may retain some errors (HERTOGEN et al., 1980). Nakhla and Lafayette were analyzed in the same irradiation as the Cl chondrites in EBIHARA et al. (1982) and Horse Creek and Mt. Egerton in WOLF et al. (1983). Chassigny was analyzed in the same irradiation (#77-4) as one analysis of Khor Temiki in WOLF et al. (1983). Abundances of the rare earth elements in Nakhla and Lafayette (Table 1b) were obtained by radiochemical neutron activation techniques at the University of Chicago, using the method of EBIHARA et al. (1982), EBIHARA (1985).

Because the SNC samples were analyzed in different irradiations, the reference analysis for BCR-1 is given for each irradiation. Nakhla and Zagami were counted on different

detectors, so the reference BCR-1 analysis is given for each detector (Table 1a). Analytical error from counting statistics (1σ) is less than half of the last significant digit given in each analysis. Upper limits are 2σ.

The analyses of Tables 1a and 1b compare well with values available in the literature (Appendix) with a few exceptions. It should first be noted that the present analyses for Os, Re, Pd and Ge are first such analyses for the SNC meteorites (except for an old determination of Os and Re in Nakhla, Appendix). Present analyses of some siderophile and chalcophile elements (Ir, Ag) are generally lower than previous analyses; we prefer the lower values as the higher values may reflect contamination. The present analyses of Rb are higher than literature values, probably reflecting the problems in radiochemical separation of Rb (see above). Cerium analyses for Nakhla and Lafayette are low compared to literature values, we suspect the present analyses are inaccurate. A few individual analyses are clearly discrepant (e.g., Ag in Nakhla). All possibly or clearly discrepant data are shown in parentheses in Table 1.

METHOD OF ESTIMATING MANTLE AND PLANETARY ABUNDANCES

To understand processes that affect the mantle abundances of siderophile and chalcophile elements, we need to determine their present-day abundances in the mantle, and relate these abundances to the inferred bulk composition of the planet. This task can be broken into smaller tasks: estimating abundances of elements in the mantle; estimating abundances in the bulk

Table 1b. Rare Earth Elements in Nakhla and Lafayette, (in ppm).

Sample run	Nakhla 80-2a	Lafayette 80-2b	BCR-1 80-2a	BCR-1 80-2b
Ce	(5.37)	(4.21)	(51.2)	(47.2)
Nd	3.38	3.12	28.8	26.7
Eu	0.223	0.188	1.67	1.67
Tb	0.115	0.104	0.763	0.932
Yb	0.386	0.307	3.21	3.09
Lu	0.0559	0.055	0.515	0.513

Analytical method described in text. See Table 1a for errors and sample data.

planet, and interpreting elemental depletions in terms of core-formation and/or late accretional processes.

Determining elemental abundances in planetary mantles requires "looking through" the differentiation and fractionation events which have generated all available samples from the Earth and SPB. A convenient way to see through silicate fractionation events is to look only at ratios of elements in basalts which behave *identically* during fractionation processes on the planet. The abundance ratios of such elements ought to be the same over the full range of mantle products, be they basalts, andesites, or peridotites. The abundance ratio thus is characteristic of the planetary mantle if our sample set is broad enough. The number of samples is not a problem for the Earth, but may be a serious limitation for the SPB; we have samples of only 9 lithologies in the SNC meteorites, and it is not known whether they sample the whole SPB or only a limited portion of it.

The element ratio determined in this way is compared to the CI chondrite ratio, yielding depletions or enrichment factors relative to the average solar system composition for condensible elements (ANDERS and EBIHARA, 1982). In general, we ratio elements of interest to refractory lithophile elements; these elements are most insensitive to nebular or core-formation processes and allow depletions in elemental ratios to be interpreted directly in terms of volatility and/or metal-silicate fractionation. This approach suffers from the limitation that the element of interest may not behave *precisely identically* to the refractory lithophile element, that is, they have varying degrees of compatibility or incompatibility, thus introducing added uncertainty in the derived depletion or enrichment factors. The choice of a reference element within a given group of elements is somewhat arbitrary. In general we select well analyzed elements yielding the best inter-element correlations. This procedure necessarily requires a subsequent correction for varying degrees of compatibility. This point will be addressed more fully in later sections.

An example of the approach is illustrated in Fig. 1a, an element-element correlation graph for Cs/La in the SNC meteorites. Within the variation of the analyses, Cs/La is approximately constant in the SNC meteorites and, therefore, in the SPB mantle. The Cs/La ratio in the SPB is less than Cs/La in CI chondrites; because La is refractory and lithophile, Cs must be depleted in the SPB. Cesium is not siderophile but is quite volatile (*e.g.*, KEAYS *et al.*, 1971), so that the depletion of Cs may be as ascribed to volatility-controlled processes during condensation and/or accretion of the SPB and its precursor materials.

We estimate mantle abundances, where possible, through element/element correlation diagrams because, like others, we do not wish to rely on specific models of basalt genesis (*e.g.*, SUN, 1982) or to estimates of 'primitiveness' (*e.g.*, JAGOUTZ *et al.*, 1979) of mantle nodules. Although the alternative approaches may be

well-founded for the Earth, they cannot be applied to the SPB, for which petrogenesis is poorly understood and for which we have no mantle samples. For the Earth, the element ratio method also allows us access to the vast literature on basalts, particularly MORB. The element ratio method applied to terrestrial basalts also permits a comparison, particularly for compatible elements, with abundances derived from mantle nodules. This comparison is illustrative of uncertainties which might exist in the estimates of mantle abundances in the SPB, from which we lack direct mantle samples.

The element-ratio method fails for some elements, specifically those which do not exhibit correlations with any refractory lithophile element. In the Earth and SPB, the compatible and indifferent elements (Table 2) must be considered separately from the more incompatible elements. For the Earth, certain chalcophile elements (*e.g.*, Ag, Re) also present a special case. For these elements, we are forced to rely either on mantle nodule data or estimated planetary compositions for normalization to refractory element abundances.

SHERGOTTITE PARENT BODY (SPB)

SPB mantle abundances

From element-element correlation diagrams, one can delineate four element groups based on mineral/melt compatibility considerations in the SPB (Table 2). The first two groups, highly incompatible and moderately incompatible, are essentially those of TREIMAN and DRAKE (1984) and WECKWERTH and WÄNKE (1984). The other two groups, indifferent and compatible, parallel similar groups in the Earth. These four groups include all minor and trace elements for which data are available except gases and Pd, Te, Cd and Ge. The last four elements are not easily interpretable within the four compatibility groups. The behavior of Ge, in particular, is surprising in view of its remarkably uniform concentration in terrestrial rocks (DEAR-GOLLO and SCHILLING, 1978; DRAKE, 1983).

Data sources for the compatibility relationships and elemental depletions in the SPB are in Table 1 (new data) and the Appendix (compilation of previously published data). A few published analyses were omitted because of gross disagreement with other analyses or because of obvious contamination.

Highly incompatible elements. The highly incompatible elements (Group 1, Table 2) in the SPB are essentially identical to those in the Earth (*e.g.*, SUN *et al.*, 1979), with a few additions (Au, Ag, and Li) and deletions (P). In studying depletions of these elements, we have taken *La as a reference element* because it is lithophile, refractory, very incompatible, and has been analyzed by many investigators. Two representative correlation graphs are given in Fig. 1. Lanthanum abundances vary by up to a factor of two in samples of a single meteorite. This variation in La content is probably a result of sample heterogeneity, and repre-

Table 2. Element Abundances in SPB Mantle, Normalized to Cl Chondritic
and a Refractory Lithophile Element.

ELEMENT	ABUNDANCE	UNCERTAINTY FACTOR	ELEMENT	ABUNDANCE	UNCERTAINTY FACTOR
Group 1 - Highly Incompatible			Group 2 - Moderately Incompatible		
Ag	0.015	2.5	Al	0.4	1.5
As	0.017	2.5	Cu	0.013	2
Au	0.002	3	Eu	1.0	1.5
Ba	2	1.7	Ga	0.1	1.5
Br	0.023	2.5	Hf	1.0	1.5
Cl	0.018	2	HREE	0.7	1.5
Cs	0.25	2	In	0.045	2
K	0.3	2	Na	0.185	2
La	=1	1.7	P	0.25	2
Li	0.4	1.7	S	0.0025	2
Rb	0.3	2	Sc	0.7	2
Sb	0.003	2	Se	0.002	2
Ta	1.5	1.7	Ti	=1	1.2
Th	1.7	1.7	Tl	0.01	2.5
U	2	2	V	0.25	2
W	0.3	2			

Group 3 - Indifferent			Group 4 - Compatible		
Bi	0.004	2.5	Cr	=0.5	
Co	0.05	2	Ir	--	
F	0.2	1.7	Ni	0.004	2
Re	0.0005	3.5	Os	--	
Zn	0.25	1.7			

Abundances taken from element-element correlation graphs like Figures
1-4. Refractory lithophile elements used for normalization are marked
by "=" in the Abundance column. Indifferent elements are of similar
abundance in all SNC meteorites; that absolute abundance is assumed to
be characteristic of the SPB mantle. Indifferent elements are normal-
ized assuming that the SPB mantle has 2xCl of refractory lithophile
elements. Chromium is near lithium in volatility (Wasson, 1985) and is
assumed to be depleted through volatility to 0.5 relative to more
refractory elements. Nickel is from the Ni/Cr ratio (Fig. 4a) adjusted
for depletion of Cr in the SPB. Uncertainty factor is the multi-
plier/divisor of the abundance value which will span all of the range
of abundance ratios in analyses of SNC meteorites.

sents the least variance one can expect in an element-element correlation diagram. Figure 1a, Cs versus La, is representative of the *best* interelement correlations seen among the highly incompatible elements. A cor-relation of similar quality, K versus La, is shown in BURGHELE et al. (1983). WÄNKE and DREIBUS (1985) show a comparable correlation of Br and La. Figure 1b, Ag versus La, is representative of the *worst* inter-
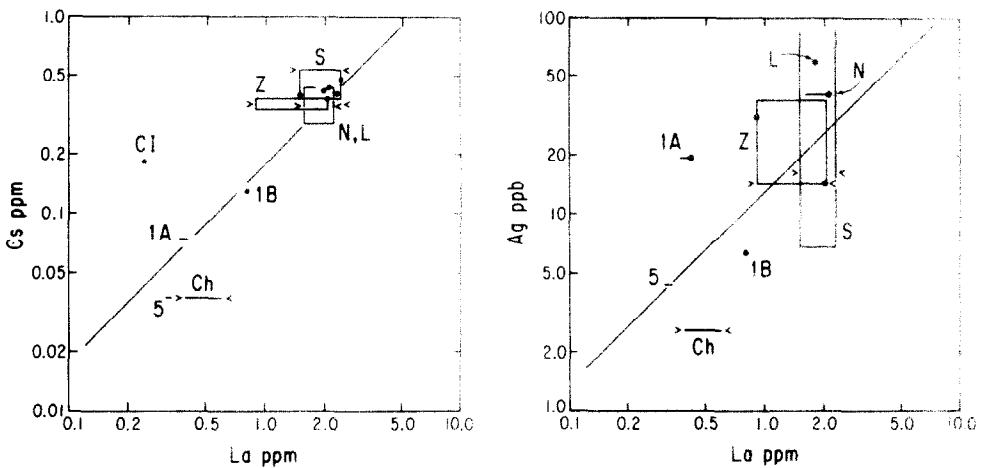

FIG. 1. Representative element correlations among the highly incompatible elements in the SPB mantle (Table 2) using La abundances as a reference. Boxes or lines show ranges of reliable analyses of each sample; solid dots are simultaneous determination of both elements by a single analyst. Analyses from Table 1a are shown here and in subsequent figures by angle signs (<, >, ∧, ∨) or by an 'X' where both elements are from Table 1a. Sample labels are: Cl, CI chondrite (ANDERS and EBIHARA, 1982); Ch, Chassigny; GV, Governador Valadares; L, Lafayette; N, Nakhla; S, Shergotty; Z, Zagami; 1A and 1B, EETA 79001 A and B; and 5, ALHA 77005. Reference lines of slope 1 are visual fits to data.

1a) Cs vs. La correlation. La in a single stone varies by a factor of 1.5, setting a limit on the accuracy of the inferred Cs/La ratio in the SPB mantle. This graph is representative of the best element correlations among highly incompatible elements.

1b) Ag vs. La correlation. Among the worst recognized correlations. Ag abundances in Lafayette and Shergotty are high and may represent contamination. Lithology 1A has assimilated xenolithic material (McSWEEN, 1983).

element correlations we have recognized as correlations. Much of the variation in this and similarly poor correlations probably stems from sample heterogeneity and contamination. It must be remembered that the non-Antarctic SNC meteorites, although all falls, have experienced more handling than most meteorites.

Moderately incompatible elements. The moderately incompatible elements in the SPB (Group 2, Table 2) are essentially the same as in the Earth (SUN *et al.*, 1979) with a few exceptions, the most notable of which is P. Figure 2 gives representative element-element correlation graphs for the moderately incompatible elements, *using Ti as a reference element.* Interpretation of Fig. 2 is analogous to interpretation of Fig. 1. For example, the SNC basalts all have a Na/Ti abundance ratio near 0.2 × Cl (Fig. 2a). Depletion of the Na must result from its volatility, as Na is neither siderophile nor chalcophile. Figure 2b, of Se *versus* Ti, shows more scatter than Fig. 2a but still demonstrates a close correlation of the two elements. The depletion of Se may be ascribed to both volatility and chalcophile affinity. BURGHELE *et al.* (1983) show correlations of

the moderately incompatible elements Al with Na and with Ga.

Nature rarely arranges its elements into such discrete groups as in Table 2, and it must be emphasized that within each element group in Table 2 are elements of varying compatibility in the SPB. For example, Nakhla is a cumulate rock consisting of 70–80% augite (BUNCH and REID, 1975; BERKLEY *et al.*, 1980) and one must expect that Nakhla would be enriched in elements which are partitioned into augite. Titanium is moderately compatible in augite (D(aug/liq) $\sim$ 0.6; IRVING, 1978), probably much more so than is Se. One should expect the Se/Ti ratio of Nakhla to be lower than in the augite-poor shergottites as is seen in Fig. 2b. Conversely, Sc is more compatible in augite than Ti (^{Sc}D(aug/liq) $\sim$ 5; IRVING, 1978) and the Sc/Ti ratio for Nakhla should be high relative to the shergottites. This prediction also is verified (Fig. 2c).

Indifferent elements. The indifferent elements (Group 3, Table 2) have approximately the same abundance levels in all of the SNC meteorites. Abundances of the indifferent elements must be buffered by
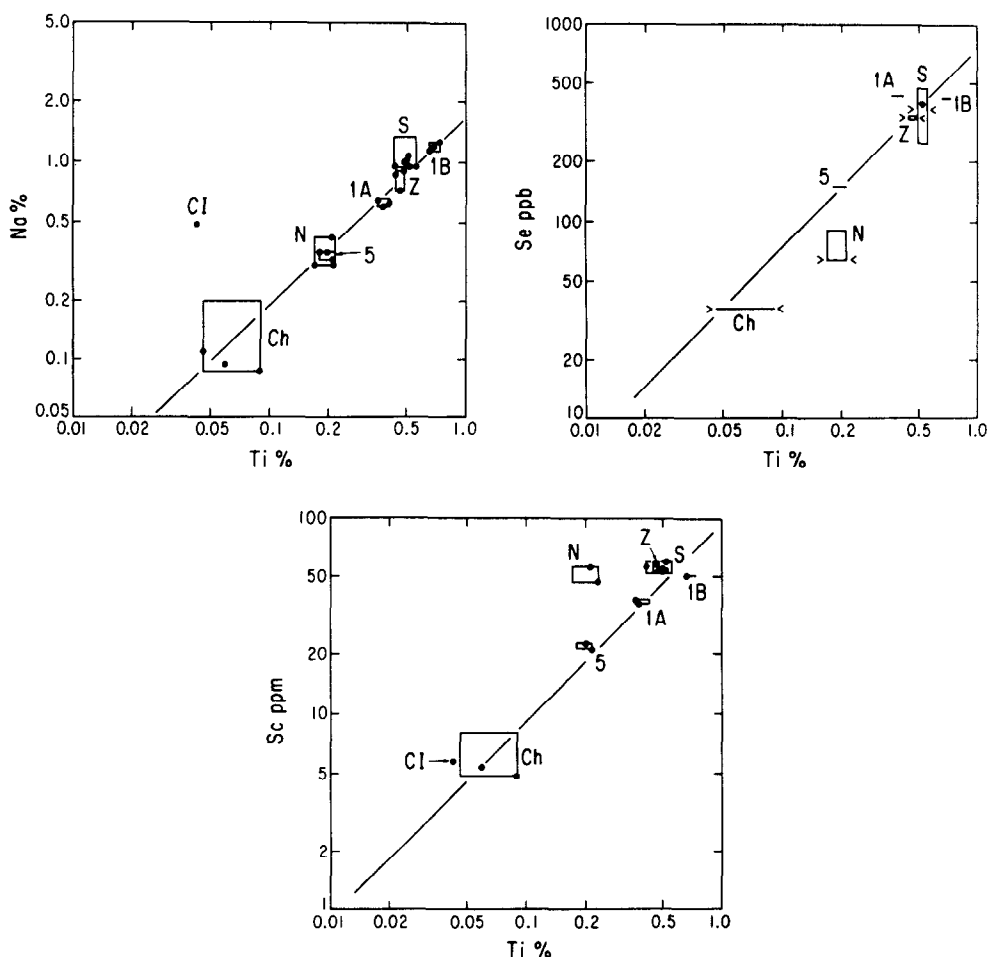

FIG. 2. Representative element correlations among the moderately incompatible elements (Table 2) in the SPB mantle. Refer to Fig. 1 caption for symbols and conventions. Except for Chassigny (Ch), Ti varies little among different analyses of an individual stone.
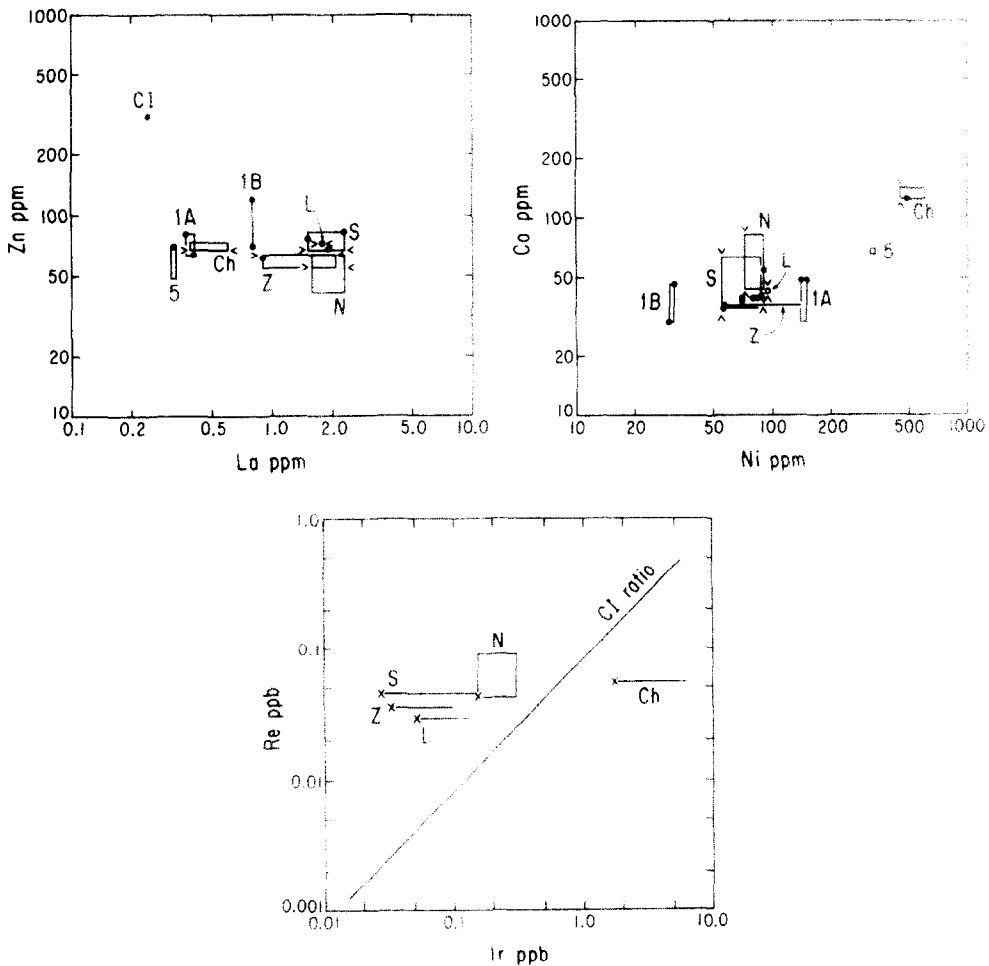
FIG. 3. Abundances of 'indifferent' elements in the SNC meteorites. Refer to Fig. 1 caption for symbols and conventions.

3a) Zn is independent of fractionation as measured by La, a strongly incompatible element.

3b) Co is independent of fractionation measured by Ni, a compatible element.

3c) Re is independent of fractionation as measured by Ir, a strongly compatible element. Re/Ir ratios are near the CI value.

a residual mantle mineral assemblage for which D(mantle/melt) $\sim$ 1. For Zn (Fig. 3a) the most important mineral is probably olivine (BOUGALT and HEKINIAN, 1974), and for Co (Fig. 3b) olivine and pyroxenes probably play a role (IRVING, 1978). Minerals which buffer Re (Fig. 3c), Bi, Tl and F are not known. Because D(mantle/melt) $\sim$ 1, abundances of the indifferent elements in the SPB mantle should be close to those in the SNC basalts.

Compatible elements. The compatible elements in the SPB (Group 4, Table 2) cannot be interpreted as easily as the incompatible or indifferent elements because we lack a truly refractory lithophile element to act as a reference. The best remaining choice for the reference element is Cr. Although Cr may exist in both divalent and trivalent states, it will be essentially entirely trivalent under the redox conditions of all SNC meteorites. Chromium is a moderately volatile element with a 50% condensation temperature (1277°K at 10^{-4} bars), marginally lower than the least refractory of the

highly refractory elements (WASSON, 1985). Nickel and Cr have similar compatibilities (Fig. 4a). Chromium is much less compatible than Ni in olivine (IRVING, 1978) so another mineral, probably chromite, must compensate. Iridium is more compatible than Cr in the SPB mantle, as indicated by the steep slope in Fig. 4b. Thus, the abundance of Ir in the SPB mantle remains indeterminate. However, the Os/Ir ratio in the SPB appears to be chondritic as shown in Fig. 4c, although Shergotty would fall well below the CI ratio if the upper limit for Os in Table 1a is correct. Until a precise Os concentration for Shergotty is determined the upper limit must be regarded with caution in that Zagami, presumably formed by the same processes as Shergotty, falls close to the CI ratio, and we know of no means to radically fractionate Ir from Os in similar processes. If this conclusion is supported by future data, the approximately chondritic Os/Ir ratio in the SPB is a property shared in common with the Earth (MORGAN *et al.,* 1981; CHOU *et al.,* 1983).
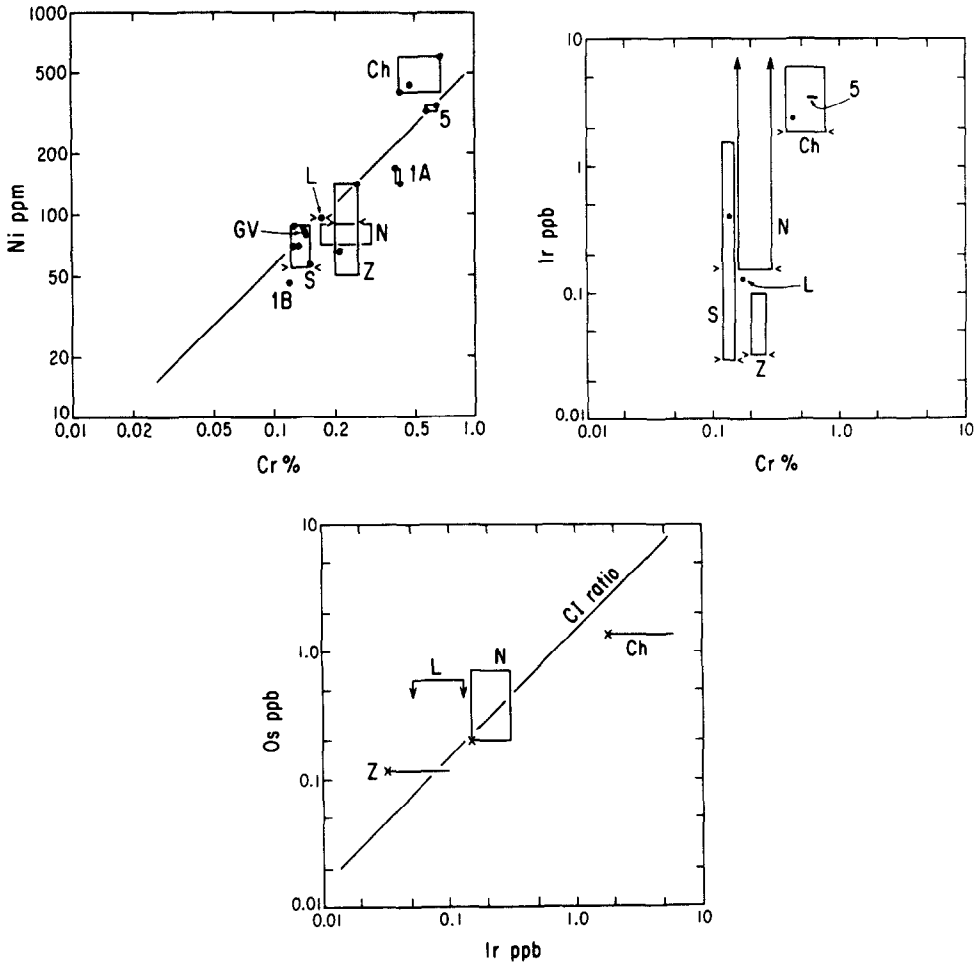
FIG. 4. Element correlations among compatible elements in the SNC meteorites. See Fig. 1 caption for symbols and conventions. Figs. 4a–4c indicate that the order of compatibility in the SPB mantle is Ni = Cr < Ir = Os. Figure 4c indicates that the Os/Ir ratio is approximately chondritic in SNC meteorites for which both elements have been analyzed and detected.

Fractionation processes in the SPB mantle

The element ratio method, if properly applied, allows one to "see through" magmatic events in the history of the SPB. Thus, inferred mantle abundances should differ from average solar system values only if (i) volatile elements are lost prior to or during planetary accretion and (ii) siderophile and chalcophile elements are fractionated during accretion or core formation. In practice the elements in each group (Table 2) are not always of identical compatibility to the reference element (La, Ti and Cr) in nature, and a third correction is needed.

That all three of these processes acted in the SPB can be seen in Fig. 5, a graph of elemental abundances in the SPB mantle (derived from graphs like Figs. 1–4) plotted against element volatility. In this diagram, the size of each bar covers the full range of element/reference element ratio in the SNC meteorites. Volatile elements are depleted relative to refractory elements of similar geochemical behavior (e.g., Cs versus La); siderophile and chalcophile elements are depleted rel-

ative to lithophile elements of similar volatility (e.g., W versus La, Sb versus Rb); and less compatible elements are somewhat enriched relative to more compatible elements (e.g., U versus La). The estimates of Fig. 5 are close to those of WÄNKE and DREIBUS (1985) and DREIBUS and WÄNKE (1985).

Our task is to deconvolve the effects of volatility, metal/silicate fractionation and igneous fractionation on elemental abundances. First, we will deduce depletions relative to CI abundances due to volatility. Second, we will examine the effects of mantle/melt fractionation that are not corrected for by the element ratio method, i.e., due to the fact that elements in each group are not of identical compatibility to the reference element. The remaining depletions of siderophile and chalcophile elements may then be interpreted in terms of proposed models of planet formation and metal/silicate separation during core formation.

Volatility. The effect of volatility on the composition of the SPB is clear from Fig. 5: elements with condensation temperatures below about 1300K are depleted relative to refractory elements. Depletions of lithophile
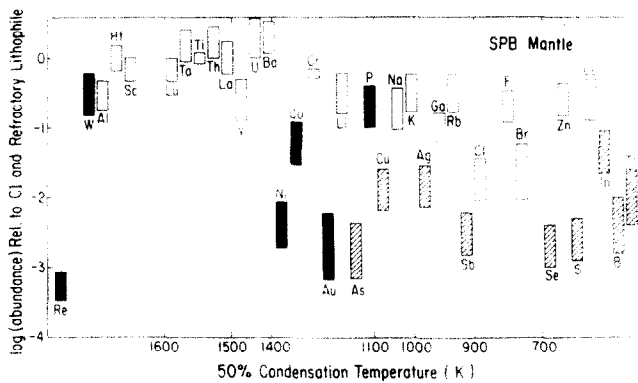
FIG. 5. Elemental abundances in the SPB mantle relative to Cl and refractory lithophile element La for highly incompatible elements, refractory lithophile element Ti for moderately incompatible elements, twice chondritic for indifferent elements (see text), and Cr for compatible elements, taken from graphs like Figs. 1–4 (data in Table 1 and Appendix). The vertical extents of bars cover full range of ratios in SNC meteorites (Figs. 1–4, Table 2) excluding obvious discrepancies. Lithophile elements shown as open boxes, siderophile elements shown as filled boxes, and chalcophile elements shown as hatchured boxes. Elements are arranged in order of decreasing condensation temperature from a gas of solar composition at 10^{-4} atmospheres (WASSON, 1985) and, consequently, temperature scale is not linear. Refractory lithophile elements (except V and Al) are present in approximately chondritic relative proportions. Volatile elements (except Cl and Br) are present at approximately 0.3 times the abundances of refractory lithophile elements. Exceptions are discussed in the text. Most siderophile and chalcophile elements are depleted more than lithophile elements of similar volatility. Mantle element abundances estimated by WÄNKE and DREIBUS (1985) fall within the ranges shown here except for Al (which they estimate to be undepleted) and In (which they estimate as depleted to $0.01 \times$ CI).

volatile elements vary from a mean value of about 0.4 × CI for Li to 0.25 × CI for Cs; In and Tl are more depleted still. (Depletions of Cl and Br are anomalous and are discussed below.) This conclusion has been reached previously by DREIBUS et al. (1982) for the SPB, and is similar to the sequence of volatile element depletions inferred for the Earth (e.g., SUN, 1982, see also following section on Earth), the Moon (e.g., WOLF and ANDERS, 1980), and the Eucrite Parent Body (e.g., MORGAN et al., 1978). The abundances of these volatile lithophile elements in the SPB will be used as a measure of volatility-induced depletions of siderophile and chalcophile elements of comparable volatility.

Chlorine and Br are exceptions to the simple volatility control described above, as they are depleted by a factor of 10 relative to other lithophile elements of similar volatility (e.g., Rb, F). The cause of these excess depletions is not known, although it must be a general phenomenon during planet formation because similar excess depletions of Cl and Br are present in the Earth (see below). It seems unlikely that these halogens are retained as 'compatible' elements during core formation and planetary differentiation because they are neither significantly siderophile nor chalcophile and because proposed mantle repositories for the halogens (amphibole and mica) accept little Br. On Earth the oceans are a significant reservoir for Cl and Br, although a similar explanation is problematical for Mars. Perhaps both Cl and Br were lost along with a hypothetical early atmosphere (WÄNKE and DREIBUS, 1985). Alternatively, Cl and Br may be more volatile during planet formation than their condensation temperatures would suggest.

Compatibility. Radio-isotope studies of the SNC meteorites give strong evidence of multiple differentiation events (e.g., GALE et al., 1975; NAKAMURA et al., 1982a,b; SHIH et al., 1982), which also should be evident in element abundances in the SPB mantle. Effects of this differentiation will be unambiguous only on the refractory lithophile elements, which are not affected by volatility or core-formation processes.

Abundances of the lithophile refractory elements are graphed in Fig. 6 against compatibility in mantle/melt processes in the Earth (SUN et al., 1979). Compatibility relationships in the SPB are somewhat different from those in the Earth (see Table 2), but we use the Earth sequence for reference. Elemental abundances in the SPB mantle are correlated with compatibility (Fig. 6), and the SPB mantle is enriched in incompatible elements (e.g., Ba versus La). Except for Al and V, silicate melt/mantle fractionation caused a maximum variation of a factor of 2 in the abundances of refractory lithophile elements. It is reasonable that volatile lithophile elements will show the same variation from compatibility, but it is not possible to separate depletions from volatility and compatibility for pairs of volatile elements like Na and K or Cs and Tl. Thus, we cannot correct for volatility better than to a factor of two.

The depletion of Al relative to Ti (Figs. 5, 6) is so large that special comment is necessary. Based on the Al/Ti ratio, three fifths of the Al is retained in the SPB mantle. For a minor element (like V) such retention is possible by partition into a mantle mineral like olivine or pyroxene, but a three fifths retention of Al seems to require an aluminous phase in the SPB man-
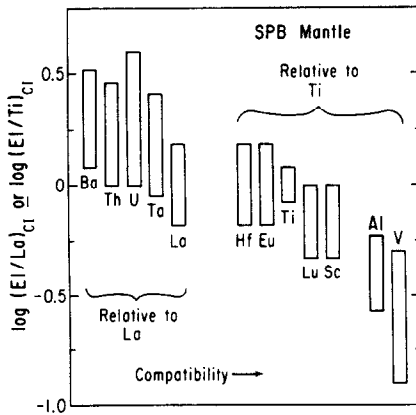
FIG. 6. Abundances of refractory lithophile elements in the SPB mantle relative to CI and index elements La or Ti. Elements are plotted in order of increasing compatibility. More compatible elements are depleted relative to less compatible elements, indicating that the element-element correlation method used here does not completely account for the effects of silicate mineral/melt fractionation.

tle. In addition, the aluminous mineral must act as a residual refractory phase, either in the immediate source of the SNC meteorites or in the precursor of the mantle source of the SNC meteorites. The aluminous phase is not likely to be plagioclase, because the Eu/Ti ratio is chondritic in the SNC meteorites. The observation might not in itself be diagnostic of plagioclase if the SNC meteorites were sufficiently oxidized that only Eu^{3+} were present. However, phase separation data (LAUL et al., 1986) show significant Eu anomalies, indicating the presence of Eu^{2+}. The choice between spinel and garnet is not clear-cut.

EARTH

Earth mantle abundances

The element-ratio method of determining elemental abundances in a planetary mantle is more difficult to apply to the Earth than the SPB because broad groups of covariant elements (like Table 2) exhibit much greater variability in incompatibility in the Earth than in the SPB. This difference in element distributions appears to stem from a fundamental difference between the source regions for basalts in the SPB and Earth: SPB basalts are derived from a mantle rich in incompatible elements (Fig. 6), while Earth MORB (and most other basalts) are derived from strongly depleted mantle (SUN et al., 1979). The depletion event produces a wide dispersion in the abundances of incompatible elements and makes a simple grouping (like Table 2) of little utility. For the Earth, we instead use pairs of elements which maintain a constant ratio in basalts. The great wealth of analyses of terrestrial rocks makes this approach possible.

Table 3 lists element abundance ratios which are nearly constant in Earth basalts (chiefly MORB). We have assumed that all refractory lithophile elements (e.g., Al, Ba, La, Nd, Sr, Ta, U, Yb) were present in

chondritic relative abundances (SUN and NESBITT, 1977) as a link among the various abundance ratios. Most of the ratios in Table 3 are firmly established and require no comment. Explanations are needed for our choices of ratios among some of the siderophile and chalcophile elements and for relating these ratios to those of other element pairs.

The distribution of some siderophile and chalcophile elements in Earth basalts and mantle samples has been enigmatic. For example, Re seems to be an indifferent element in basalts, but its average abundance in basalts is seven times that in mantle samples (CHOU et al., 1983). MORGAN and BAEDECKER (1983) found that Re, S, and Se abundances are correlated in one suite of mantle xenoliths, and we have extended their correlation to include Ag, other mantle nodules, and basalts (Figs. 7a, b, c). These graphs define the ratios Se/Re, Se/Ag, and S/Ag in Table 3. Few basalts or nodules have been analyzed for all of these elements, so our data set differs from graph to graph. Abundances of these four elements show no correlations with incompatible elements (e.g., La, Fig. 7d) or compatible elements (e.g., Ir, Fig. 4b of CHOU et al., 1983). Neither Au nor Pd are correlated with these four elements (CHOU et al., 1983).

Interpretation of the correlations of Ag, Re, S and Se is both obvious and enigmatic. The Earth's mantle must contain some phase (or phases) which carries these elements and is dissolved quantitatively or without element fractionation into basalt during partial melting. The lack of correlation with compatible or incompatible elements suggests that these four elements are distributed independently of partial melting or mantle metasomatism. A possible carrier phase is a

Table 3. Chondrite-normalized abundance ratios in the Earth's mantle, based on element-element correlations.

Element	Ratio	Abundance	Uncertainty Factor	Source*
Ag	Ag/Re	10	2	9
Br	Br/Ba	0.003	3	6
Cl	Cl/Ba	0.023	2	6
Cs	Cs/Ba	0.014	1.5	4
F	F/Sr	0.11	1.5	6
Ga	Ga/Al	0.2	1.5	1,2
Ge	Ge/Si	0.02	1.5	1
In	In/Yb	0.025	1.5	3
K	K/U	0.14	1.5	8
Mo	Mo/Nd	0.02	2.5	5
Na	Na/Ti	0.03	2	7,10
Ni	Ni/Cr	0.2	2.5	10
Os	Os/Ir	1.0	1.15	3
P	P/Nd	0.03	2	5
P	P/Sr	0.05	2	6
Rb	Rb/Ba	0.09	1.5	4
S	S/Re	0.5	3	9
Sb	Sb/U	0.008	2	3
Se	Se/Re	0.5	2	9
Sn	Sn/La	0.03	2	10
W	W/U	0.05	2.5	5

Uncertainty factor is the multiplier/divisor to the abundance ratio cited which will span the reasonable range of observed abundance ratios.

*Sources for data are: (1) DeArgollo and Schilling, 1978; (2) Drake et al., 1984; (3) Hertogen et al., 1980; (4) Hofmann and White, 1983; (5) Newsom and Palme, 1984; (6) Schilling et al., 1980; (7) Sun and Nesbitt, 1977; (8) Langmuir et al., 1977; (9) this paper; and (10) unpublished data.
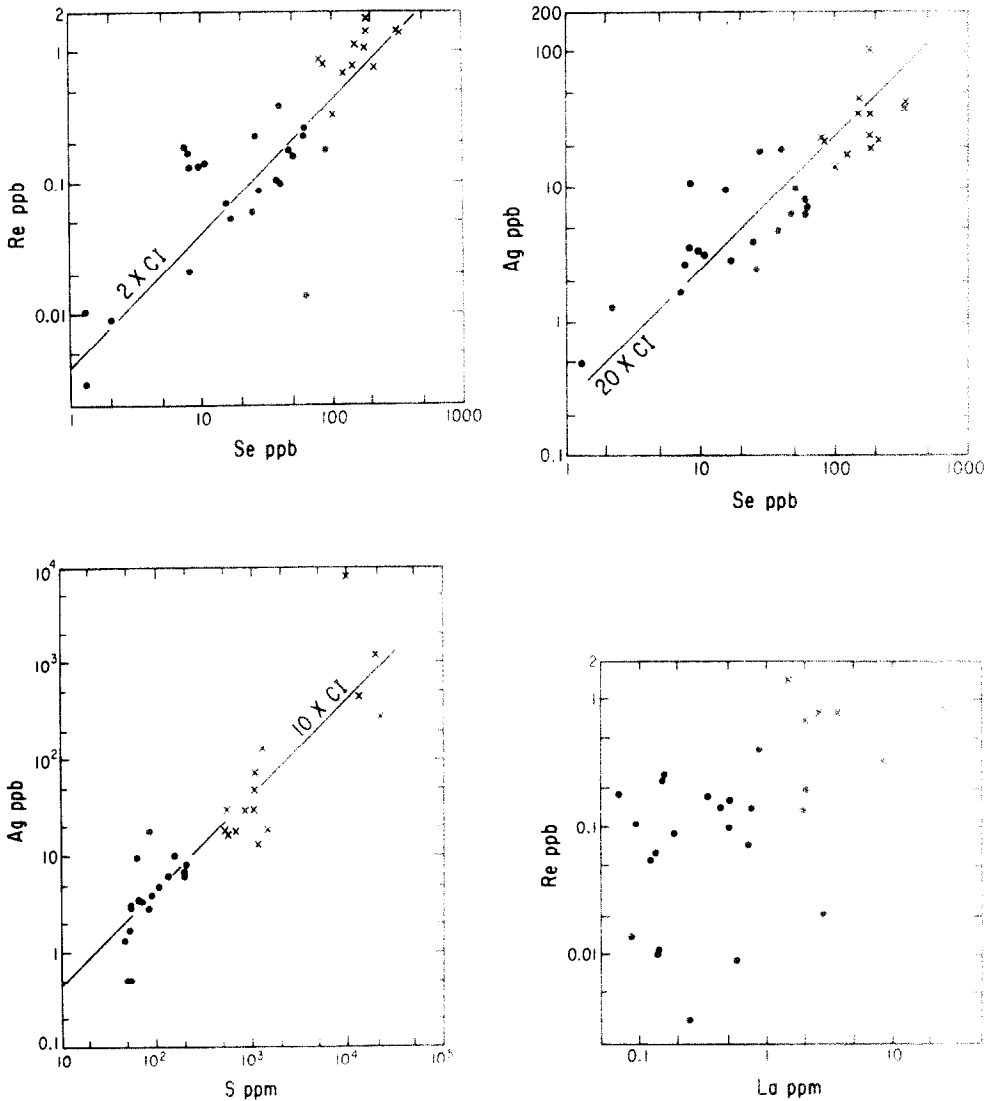
FIG. 7. Correlations among some chalcophile elements in Earth basalts, 'X', and mantle nodules '●'. Abundances of Ag, Re, S. and Se do not correlate with degree of fractionation or LIL-enrichment as given by La abundances (Fig. 7d). Data in these figures from LAUL et al. (1972), KEAYS and SCOTT (1976). JAGOUTZ et al. (1979), HERTOGEN et al. (1980), KURAT et al. (1980), MORGAN et al. (1980, 1981), BASALTIC VOLCANISM STUDY PROJECT (1981), and KEAYS and CAMPBELL (1981).

sulfide melt, as was proposed by MITCHELL and KEAYS (1981) on petrographic grounds. But Mitchell and Keays found that their sulfide melt also carried most of the Ir, Pd and Au in the mantle nodules, whereas we do not find these elements to be correlated with Ag, Re, S and Se. The identity of the phase containing Ag, Re, S and Se remains obscure.

To relate the abundances of Ag, Re, S and Se to the incompatible elements of Table 3, one must know the abundance of one of the elements relative to a refractory incompatible lithophile element in the Earth's mantle. Based on the Fe/Mg ratio of komatiites and undepleted mantle nodules, the abundance of refractory incompatible lithophile elements may be estimated as $2.5-3 \times$ CI (BASALTIC VOLCANISM STUDY PROJECT, 1981, p. 641). The Re abundance in the Earth's mantle may be estimated as $0.007 \times$ CI from: the average abundances of Ir and Os in mantle samples (0.007

$\times$ CI: JAGOUTZ et al., 1979; MORGAN et al. 1981; CHOU et al., 1983); and a chondritic Os/Re ratio in the mantle (ALLÈGRE and LUCK, 1980). Thus, we have based the abundances of Ag, Re, S and Se on a value of $0.0025 \times$ CI for the Re/La ratio.

The ratios of Table 3 are graphed in Fig. 8 as a function of elemental volatility, as was done in Fig. 5 for the SPB mantle abundances. Elemental abundance ratios inferred here are (for the most part) not significantly different from those inferred in other recent investigations (Fig. 8), lending credence to the element ratio method. In particular, abundances of Ag, S, and Se are also near most recent estimates, lending support to our interpretation of their correlations.

Relative to chondrites and refractory lithophile element abundances, the Earth's mantle is depleted in volatile, siderophile and chalcophile elements (Fig. 8) Depletions of volatile lithophile elements are a mono-
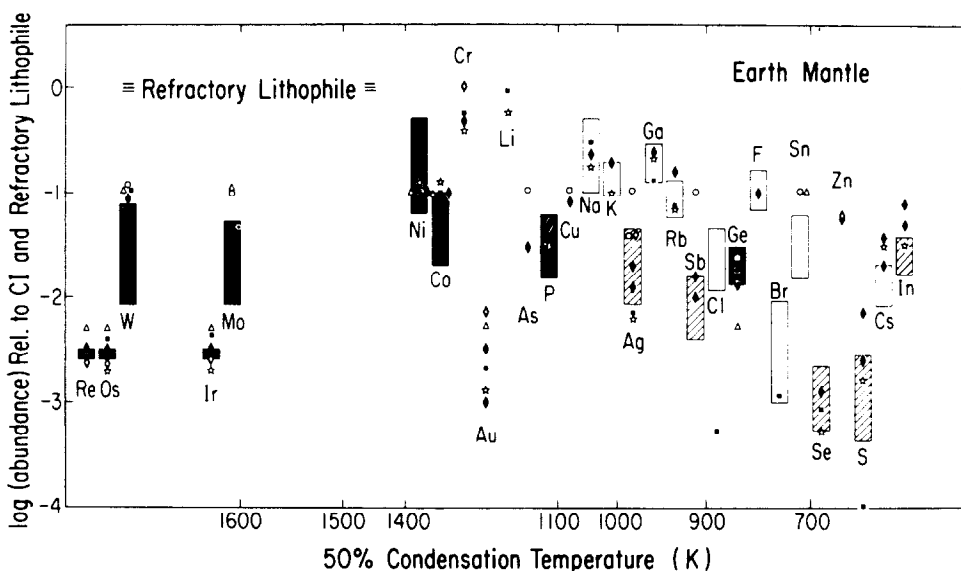
FIG. 8. Elemental abundances in the Earth's mantle inferred mostly from basalts relative to refractory lithophile incompatible elements and CI (see Table 3 for details). Temperature scale (as in Fig. 5) is not linear. Abundances of Ag, S, and Se are based on Figs. 7a–c and an abundance for Re from CHOU *et al.* (1983). Ir/Os is from MORGAN *et al.* (1981) and CHOU *et al.* (1983). Re/Os is from ALLÈGRE and LUCK (1980). Ni is from Ni/Cr ratio, ignoring inferred depletion of Cr in the mantle (DREIBUS and WÄNKE, 1979). Co is range of abundances in mantle nodules and MORB basalts. Shading conventions and horizontal axis as in Fig. 5. Vertical extent of bars covers full range of inferred elemental abundance ratios. Other estimates of the composition of the Earth's mantle are shown as follows: open circle, CHOU (1978); open diamond, MORGAN *et al.* (1980, 1981); open triangle, ARCULUS and DELANO (1981); filled square, WÄNKE (1981); filled diamond, SUN (1982); open star, ANDERSON (1983).

tonic function of element condensation temperature except for Cl and Br, which are also anomalously depleted in the SPB. Chalcophile and siderophile elements are depleted in excess of what their volatility would imply. The excess depletions are attributed to metal/silicate and metallic liquid/silicate fractionation, presumably during core formation. Imperfect compatibility compared to the reference element is not significant in the case of Earth due to our selection of a wide variety of index elements.

COMPARISON OF THE MANTLES OF THE EARTH AND SPB

Elemental abundances in the mantles of the Earth and SPB, shown in Figs. 5 and 8, are the basis for comparison of processes which acted during accretion and early differentiation of the two planets. Our interest centers on the siderophile and chalcophile elements. Elemental abundances in the two planetary mantles are broadly similar: both are relatively depleted in volatile elements compared to refractory elements, and both show additional depletions in the siderophile and chalcophile elements. It is the differences between the two sets of abundance patterns that provide insight into the accretion and evolution of the two planets.

Volatile elements

In the Earth, the abundance pattern of lithophile elements is a monotonic function of volatility with Cs depleted by a factor of 100 relative to refractory lithophile elements (ignoring Br and Cl which appear to

be anomalous as discussed earlier). The depletions in the SPB are different. The lithophile elements Li through Cs are depleted by a factor of 3 relative to refractory lithophile elements (again ignoring Br and Cl). The most volatile elements, In and Tl, are further depleted to factors near 50, but some of this depletion may be due to the moderately chalcophile behavior of both elements.

Siderophile elements

Noble siderophile elements are greatly depleted in the mantles of both the Earth and SPB, although data for the SPB are limited to Au and Re. Abundances of noble siderophile elements in the Earth's mantle may be higher than in the SPB mantle by a factor of five or so. In both planetary mantles, the noble siderophile elements appear to be present in approximately CI relative proportions. For the Earth, the CI ratio is well constrained (*e.g.*, ALLÈGRE and LUCK, 1980; CHOU *et al.*, 1983); for the SPB a nonchondritic Au/Re ratio cannot be excluded.

Although Ga behaved as a siderophile element during core formation in the moon and the eucrite parent body (DRAKE *et al.*, 1984), in the Earth and the SPB it acted as a lithophile element, in accord with the more oxidized states of the Earth and SPB compared to the Moon and EPB. In the Earth, depletion of Ga relative to Al (Fig. 8) can be ascribed entirely to the volatility of Ga; lithophile elements with volatilities near that of Ga (*e.g.*, Na, K, Rb) have essentially the same CI-normalized abundances as Ga. In the SPB mantle Al is

depleted (Fig. 6), and we may assume that Ga is depleted by the same process. The ratio Ga/Al = 0.3 (Table 2) is identical to the ratios defining the abundances of lithophile elements which are as volatile as Ga (Na, K, Rb; Fig. 5). Thus, depletion of Ga in the SPB mantle can be ascribed to volatility and mineral/melt fractionation; there is no evidence that Ga was siderophile during core formation in the SPB.

Phosphorus and W may be considered together because both are moderately siderophile and are incompatible in common mantle minerals. Tungsten is more siderophile than P for reasonable conditions of core formation (e.g., JONES and DRAKE, 1986); after correction for the volatility of P, W is more depleted than P in the mantles of the Earth and SPB (Figs. 9, 10). Tungsten and P are both depleted less in the mantle of the SPB than the mantle of the Earth, confirming the suggestion that the SPB is more oxidized than the Earth (DREIBUS et al., 1982; BURGHELE et al., 1983). Phosphorus in the SPB mantle is undepleted relative to lithophile elements of similar volatility (e.g., Li, Na: Fig. 5) and therefore did not act as a siderophile element during core formation in the SPB.

Nickel and Co will be considered together, because the Ni/Co ratio has been important in studies of the Earth's mantle. Both elements are sufficiently refractory that depletion through volatility need not be considered. Nickel and Co in both planetary mantles are depleted below their Cl values, consistent with indigenous metal/silicate fractionation events. But the Ni/Co ratios in the two planetary mantles are radically different. In the Earth's mantle, the Ni/Co ratio is approximately chondritic, a conclusion reached by all other investigators (Fig. 8). Our Ni abundance is derived from the
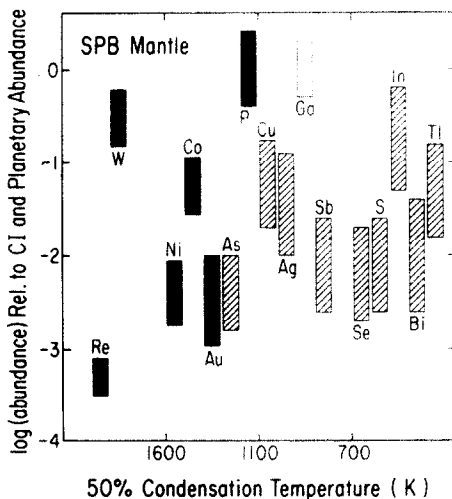

FIG. 10. Abundances of siderophile and chalcophile elements in the Earth's mantle relative to Cl and lithophile elements of similar volatility. Conventions, methods and shadings are as on Fig. 9.

Ni/Cr ratio in basalts (Table 3); if Cr is depleted in the Earth's mantle (e.g., DREIBUS and WÄNKE, 1979; JA-GOUTZ et al., 1979), then the Ni/Co ratio inferred from basalts is almost exactly chondritic. In contrast to the Earth, the Ni/Co ratio in the SPB mantle is near ¹/₁₀ of the Cl ratio (Fig. 5); if Cr is depleted in the SPB mantle, the Ni/Co ratio becomes still smaller. The difference between the Ni/Co ratios in the Earth and SPB suggests significant differences in planetary evolution.

Chalcophile elements

Sulfur and Se occur principally in sulfide minerals or S-rich melts at the redox conditions of planetary differentiation, and it is convenient to consider them separately from other chalcophile elements which have more lithophile affinities. Sulfur and Se are depleted in the mantles of the Earth and SPB, but the S/Se ratio is approximately chondritic in both cases (Figs. 5, 8). Abundances of S and Se in the two mantles are very similar at about 10^{-3} relative to Cl and refractory lithophile elements. However, relative to lithophile elements of similar volatility (F, Sn, Zn, Cs), S and Se are much more depleted in the SPB mantle than the Earth's mantle (Figs. 9, 10). Relative to volatile lithophile elements, only one percent of the original S and Se remains in the SPB mantle, while approximately five percent remains in the Earth's mantle.

The other chalcophile elements (As, Cu, Ag, Sb, In, Bi, and Tl) are variably depleted in the mantles of the Earth and SPB (Figs. 5, 8). In general, the SPB mantle is more depleted in these elements than is the Earth's mantle. Relative to Cl and refractory lithophile elements, only Ag and In have similar abundances in the two mantles. The greater depletion of chalcophile elements in the SPB mantle was also noted by WÄNKE and DREIBUS (1984). If one considers depletion factors relative to Cl and lithophile elements of similar volatility (Figs. 9, 10) then the SPB is strikingly depleted

FIG. 9. Abundances of siderophile elements (black bars) and chalcophile elements (hatchured bars) in the SPB mantle, relative to: (1) Cl; and (2) abundances of lithophile elements of similar volatility (see Fig. 5). Depletions on this figure are due to metal/silicate fractionation alone. Gallium is relative to Al, because Al and Ga follow each other closely (DEAR-GOLLO and SCHILLING, 1978) and Al is depleted in the SPB mantle (Fig. 5).
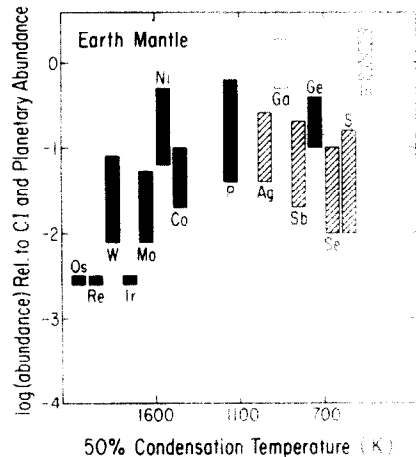
in chalcophile elements compared to the Earth. Only Ag abundances are then similar in the two planetary mantles.

DISCUSSION

Any model of the abundances of siderophile and chalcophile elements in the mantles of the Earth and SPB must fit two independent sets of constraints: moderately siderophile and chalcophile elements are depleted to varying degrees; and strongly siderophile and chalcophile elements in both mantles appear to be present in approximately chondritic relative abundances. Two models will be considered for each set of constraints: heterogeneous accretion and inefficient core formation.

The heterogeneous accretion hypothesis for the Earth as formulated by WÄNKE (1981), holds that core formation continues throughout accretion and that the composition of the accreted matter becomes more oxidizing and volatile-rich over time. Approximately the last one percent accreted is not affected by metal/silicate fractionation because metal is no longer stable, leading to chondritic relative abundances of the noble siderophile and strongly chalcophile elements.

The inefficient core formation hypothesis as formulated by JONES and DRAKE (1986) holds that the abundances of siderophile and chalcophile elements is a consequence of core formation in which separation of solid and liquid metal phases from the silicate mantle is not perfect. Small quantities of solid metal and metallic liquid are trapped in the silicate mantle, giving the mantle its chondritic relative proportions of the most siderophile and chalcophile elements. These two hypotheses are not mutually exclusive. For example, the late stage of accretion in the inefficient core formation hypothesis might result in failure to achieve perfect equilibrium between metal and silicate and, hence, would resemble a 'chondritic veneer'. The critical factor in deciding among these hypotheses may be the timing of core formation relative to accretion (e.g., STEVENSON, 1981).

Earth

The heterogeneous accretion hypothesis is at first sight attractive in that it provides a ready explanation for approximately chondritic element ratios such as Ni/Co, Mo/W, Ir/Os, Os/Re, and S/Se (Figs. 5, 8–10). Many aspects of this model are not yet quantified, however, including the proportion and composition of the accreting material as a function of time.

For example, during heterogeneous accretion with continuous core formation, Co and Ni will be fractionated from each other because their partitioning among solid and liquid metal and silicate phases are different. For example, at 1250°C and $\log fO_2 = -12.5$ to -13.0, the solid metal/liquid silicate partition coefficient for Ni is 6600 while for Co is 350 (JONES and DRAKE, 1985). Thus, more Ni than Co (relative to CI) will be removed to the core, and the resultant mantle

will have a subchondritic Ni/Co ratio. For Ni and Co to remain unfractionated, the oxygen fugacity of the accreting material must rise to a significantly high value to cause Ni and Co to be retained in silicate at the expense of metal. Given a mantle that does have a chondritic Ni/Co ratio, it seems impossible to reproduce at present mantle abundances of W at $0.11 \times CI$ at approximately $0.2 \times CI$ absolute abundances and of Mo at $0.064 \times CI$ (JONES and DRAKE, 1986). Molybdenum is much more siderophile than W, so fractionation that lowers Mo from $0.2 \times CI$ abundance to $0.064 \times CI$ abundance has essentially no effect on W.

The inefficient core formation hypothesis is able to reproduce abundances of a subset of siderophile and chalcophile elements adequately (JONES and DRAKE, 1984), but cannot reproduce all siderophile and chalcophile elements simultaneously (JONES and DRAKE, 1986).

We are left with the dissatisfying conclusion that, at present, no hypothesis quantitatively explains the abundances of siderophile and chalcophile elements in the Earth's mantle.

Shergottite parent body

Unlike the Earth, few siderophile and chalcophile elements in the SPB mantle are present in chondritic relative proportions (Figs. 5, 9), suggesting that different metal/silicate fractionation mechanisms may have operated in the SPB and Earth. WÄNKE and DREIBUS (1985) have argued that equilibrium between silicate and sulfide (presumably sulfide melt) can account for the distribution of siderophile and chalcophile elements in the SPB mantle. We agree, in general, that core formation in the SPB may be modelled as an equilibrium partitioning process, particularly with respect to Ni ad Co. Nickel is partitioned more strongly into solid metal and sulfide liquid than is Co, (SCHMITT et al., 1984; JONES and DRAKE, 1986), so equilibrium separation of metal and sulfide melt from a silicate mantle should leave the mantle more depleted in Ni than Co. This prediction is in agreement with inferred abundances in the SPB (Figs. 5, 9) if small fractions of solid metal and sulfide liquid remain trapped in the SPB mantle.

However, this model may not explain Mo abundances adequately. Single Mo analyses are available for Nakhla (WEINCKE, 1978) and Shergotty (LAUL et al., 1986), which give Mo/Nd = 0.02–$0.04 \times CI$. If this Mo/Nd ratio is characteristic of the SPB mantle (see NEWSOM and PALME, 1984), the equilibrium models fail because they predict a value of Mo which is too low by an order of magnitude. Even in a generous case of 30% partial melting and a core composed entirely of sulfide liquid constituting 15% of the planet, the model Mo abundance is a factor of 4 too low. Caution must be exercised in interpreting limited Mo data, however. In the Earth and Moon (NEWSOM, 1985) there is considerable scatter in the Mo-Nd correlation and the available data for Shergotty and Nakhla could both be extremes. In addition it cannot be excluded

that Mo may behave differently in the Earth and SPB, as has been shown for P (Figs. 5, 8). Further data on Mo abundances in the SNC meteorites are needed before the hypothesis of equilibrium between metal and silicate phases in the SPB can be confirmed or discarded.

The low Re abundance inferred in the SPB mantle (Figs. 3c, 5, 9; Table 2) provides strong constraints both on the phases which separate to the core in the inefficient core formation hypothesis, and on the volume of possible late chondritic veneer accreted to the SPB in the heterogeneous accretion hypothesis. Using the partition coefficients of JONES and DRAKE (1986), a core of pure sulfide liquid will not remove enough Re from the SPB mantle to yield the observed Re abundance. At least 5% of the SPB must separate as solid metal to the core to model the abundance of Re. Similarly, the low abundance of Re is an upper limit on the proportion of any postulated late chondritic veneer that can be mixed into the SPB mantle. If the SPB mantle has refractory lithophile elements at 2 × CI, then the absolute abundance of Re in the mantle is near 0.001 × CI. Thus, any late chondritic veneer can constitute at most 0.1% of the SPB mantle. This contrasts with the Earth, where approximately 1% of chondritic veneer is postulated by WÄNKE (1981).

CONCLUSIONS

While displaying many similar features, abundances of chalcophile and siderophile elements in the mantles of the Earth and SPB display a number of significant differences. Specifically, the mantle of the Earth has approximately chondritic ratios of a number of elements including the noble siderophile elements at approximately 0.007 × CI abundances and Ni/Co at 0.05–0.10 × CI abundances. In contrast, the mantle of the SPB may have approximately chondritic noble siderophile element ratios at less than 0.001 × CI abundances and a Ni/Co ratio that is clearly non-chondritic (approximately $^{1}/_{10}$ of the chondritic ratio). Although both planetary mantles have S and Se at approximately 10^{-3} × CI relative to refractory lithophile elements, correction for the complements of volatile elements in the two planets shows that the SPB mantle is strongly depleted in S and Se relative to the Earth's mantle (Figs. 9, 10).

Although both the heterogeneous accretion hypothesis and the inefficient core formation hypothesis have attractive features when accounting for siderophile and chalcophile element abundances in the Earth's mantle, neither is successful if considered in detail (JONES and DRAKE, 1986). Regardless, it appears that the SPB underwent accretion and/or differentiation processes which differ from those in the Earth.

If the heterogeneous accretion hypothesis is broadly correct for the Earth (its present quantitative failure might simply reflect our inability to model the process adequately) then either the SPB accreted differently (i.e., homogeneously), or else it was homogenized sub-

sequent to accretion but prior to core formation. Why two terrestrial planetary bodies would behave so differently is unclear, particularly if the identification of Mars as the SPB is correct.

If the inefficient core formation hypothesis is broadly correct for the Earth (again, its present quantitative failure would be ascribed to our inability to model the process adequately) then differences in siderophile and chalcophile element abundances in the mantles of the Earth and SPB might simply reflect the greater relative mass of S available for solution in metallic liquid in the SPB. Metal/silicate equilibrium in the SPB might reflect principally a greater amount of S-bearing metallic liquid separating to make the SPB core compared to Earth.

Further progress in interpreting SPB mantle abundances in terms of accretional and differentiation processes will be facilitated by determining the abundance of Mo in the other SNC meteorites. If the abundance ratio Mo/Nd in the SPB mantle is confirmed to be as high as 0.04 × CI, it will be necessary to abandon the currently successful hypothesis of equilibrium between metal and silicate for the SPB. In contrast, a ratio lower by a factor of seven would be consistent with this hypothesis. The importance of these measurements for understanding how the terrestrial planets accreted cannot be overemphasized.

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APPENDIX: CHEMICAL COMPOSITIONS OF 'SNC' METEORITES

This appendix is a compilation of whole-rock chemical analyses of 'SNC' meteorites (ALHA 77005, Chassigny, EETA 79001, Governador Valadares, LaFayette, Nakhla, Shergotty, Zagami) published between 1955 and March, 1985. The compilations of B. MASON (*Handbook of Elemental Abundances in Meteorites*, 1971) and D. MITTLEFEHLDT (unpublished) were indispensible references. Any omissions are regretted. In some cases (*e.g.*, ALHA 77005), a single analysis

may have been published more than once without adequate citations.

For each meteorite, elements are arranged by the periodic table. For each element, analyses are arranged in reverse chronological order (*i.e.*, most recent is first), and the reference number is given in parentheses.

ALHA 77005

Li	ppm:	1.31(5); 1.58(10)
C	ppm:	82(5)
F	ppm:	219(5)
Na	% :	0.36(4); 0.325(5); 0.35(11)
Mg	% :	16.0(4); 16.70(5); 16.0(11)
Al	% :	1.6(4); 1.37(5); 1.6(11)
Si	% :	21.(4); 20.14(5); 20.3(11)
P	% :	0.157(5); 0.179(11)
S	% :	0.060(5)
Cl	ppm:	14(5)
K	% :	0.023(3); 0.023(4); 0.022(5); 0.0233(10); 0.023(11); 0.021(17)
Ca	% :	2.7(4); 2.00(5); 2.4(10); 2.7(11); 2.10, 2.02(12)
Sc	ppm:	22(4); 21.1(5); 22(11)
Ti	% :	0.2(4); 0.32(5); 0.2(11)
V	ppm:	158(4); 158(11)
Cr	% :	0.659(5); 0.57(11)
Mn	% :	0.34(4); 0.354(5); 0.34(11)
Fe	% :	15.71(4); 15.51(5); 15.7(11)
Co	ppm:	69(4); 69.5(5); 70(11); 67.2(17)
Ni	ppm:	320(4); 335(5); 320(11)
Cu	ppm:	5.5(4); 5.47(17)
Zn	ppm:	49(4); 71(5); 49(17)
Ga	ppm:	6.1(4); 7.5(5); 6.1(17)
As	ppb:	1.4(4); 22(5); 1.37(17)
Se	ppb:	0.15(4); 0.15(17)
Br	ppb:	69(5)
Rb	ppm:	0.63(4); 0.626(5); 0.828, 0.775, 0.713, 0.783(10); 0.633(13); 0.63(17)
Sr	ppm:	15(4); 100(5); 14.1, 14.1, 13.0, 12.56(10); 16(11), 6.2, 6.3(12); 8.06(13)
Ag	ppb:	4.4(4); 4.4(17)
Cd	ppb:	6.0(4); 6.0(17)
In	ppb:	11(4); 11(17)
Sb	ppb:	0.68(4); 0.7(17)
Te	ppb:	0.5(4); 0.45(17)
I	ppm:	1.72 (5)
Cs	ppb:	38(4); 38(5); 38(17)
Ba	ppm:	5.3(4); 4.53(10); 6.0(1.1); 2.4, 2.3(12); 3.45(13)
La	ppm:	0.32(4); 0.32(5); 0.314(10); 0.33, 0.33(11); 0.1812(13)
Ce	ppm:	0.84(4); 1.09(5); 0.742(10); 0.94(11); 0.758(13)
Pr	ppm:	0.13(4); 0.13(11)
Nd	ppm:	0.82(4); 1.15(5); 0.7952, 0.8684, 0.762(10); 0.88(11); 0.399(13)
Sm	ppm:	0.46(4); 0.42(5); 0.4748, 0.5107, 0.450(10); 0.46, 0.46(11); 0.226(13)
Eu	ppm:	0.22(4); 0.20(5); 0.224(10); 0.21, 0.23(11); 0.1187(13)
Gd	ppm:	0.92(4); 0.92(11); 0.440(13)
Tb	ppm:	0.18(4); 0.17(5); 0.18(11)
Dy	ppm:	1.16(4); 0.96(5); 1.16(10); 1.1(11); 0.569(13)
Ho	ppm:	0.27(4); 0.22(5); 0.27(11)
Er	ppm:	0.66(4); 0.659(10); 0.336(13)
Tm	ppm:	0.090(4); 0.08(5); 0.09(11)
Yb	ppm:	0.55(4); 0.52(5); 0.541(10); 0.53, 0.53(11); 0.315(13)
Lu	ppm:	0.077(4); 0.073(5); 0.0742(10); 0.078, 0.080(11); 0.0461(13)
Hf	ppm:	0.58(4); 0.55(5); 0.58(11)
Ta	ppb:	26(5)
W	ppb:	84(5)
Ir	ppb:	3.5(5)
Au	ppb:	0.29(4); 0.3(5); 0.288(17)

Tl ppb: 1.7(4); 1.7(17)
Th ppb: 59(17)
U   ppb: 18, 40(4); 40(11); 18(17)

CHASSIGNY

Li ppm: 1.3(5)
B   ppm: 6.3(14)
C   ppm: 847(5)
F   ppm: 14.7(5)
Na % : 0.095(5); 0.085(26); 0.11(31); 0.099, 0.010(45); 0.20(55); 0.082(56)
Mg % : 19.06(5); 18.2(26); 19.80(31); 19.72(45); 19.27(55); 19.40(56)
Al % : 0.37(5); 0.34(26); 0.19(31); 0.25(45); 0.62(55); 0.71(56)
Si % : 17.84(5); 17.30(31); 17.44(45); 17.20(55); 17.50(56)
P   % : 0.025(5); 0.018(31); 0.05(55); 0.03(56)
S   % : 0.012(3)
Cl ppm: 34(5)
K   % : 0.034(5); 0.038(26); 0.027(31); 0.033(45); 0.13(55); 0.017(56)
Ca % : 0.43(5); 0.51(26); 1.42(31); 0.54(45); 0.43(55); 0.37(56)
Sc ppm: 5.4(5); 4.8(26); 5.6, 8(45)
Ti % : 0.060(5); 0.09(26); 0.40(31); 0.50(45); 0.10(56)
V   ppm: 34(26)
Cr % : 0.430(5); 0.38(26); 0.57(31); 0.45, 0.479(45); 0.53(55); 0.67(56)
Mn % : 0.407(5); 0.40(26); 0.413(31); 0.43(45); 0.19(55); 0.57(56)
Fe % : 21.07(5); 20.0(26); 21.34(31); 20.82, 23.0(45); 21.07(55); 20.64(56)
Co ppm: 126(5); 124(26); 141, 100(45)
Ni ppm: 480(5); 400(26); 475(45); 600(56)
Cu ppm: 2.6(5)
Zn ppm: 74(5)
Ga ppm: 0.7(5)
As ppb: 8(5)
Br ppb: 66(5)
Rb ppm: 0.4(30)
Sr ppm: 7.2(30)
Y   ppm: 0.64(30)
Zr ppm: 1.5(30)
Nb ppm: 0.32(30)
Ba ppm: 7.1(30); 8(45)
La ppm: 0.59(5); 0.60(26); 0.39(30)
Ce ppm: 1.12(30)
Pr ppm: 0.13(30)
Nd ppm: 0.7(5); 0.54(30)
Sm ppm: 0.16(5); 0.14(26); 0.11(30)
Eu ppm: 0.052(5); 0.045(26); 0.038(30)
Gd ppm: 0.11(30)
Tb ppm: 0.04(5); 0.02(30)
Dy ppm: 0.27(5); 0.12(30)
Ho ppm: 0.058(5); 0.03(30)
Yb ppm: 0.12(5); 0.10(26); 0.10(30)
Lu ppm: 0.018(5); 0.012(26)
W   ppb: 46(5)
Ir ppb: 2.4(5); 6(26)
Au ppb: 1.0(5); 6(26)
Pb ppb: 1000(30)
Th ppb: 57(30)
U   ppb: 21(30)

EETA 79001A

Li ppm: 4.54(5)
C   ppm: 36(5); 20(6)
F   ppm: 39(5)
Na % : 0.65, 0.64, 0.70(4); 0.607(5); 0.62(6)

Mg % : 9.83, 9.83, 9.95(4); 9.84(5); 10.01(6)
Al % : 2.96, 2.96, 3.28(4); 2.84(5); 3.01(6)
Si % : 23(4); 22.71(5); 22.67(6)
P   % : 0.24(5); 0.28(6)
S   % : 0.160(5); 0.18(6)
Cl ppm: 26(5)
K   % : 0.0237, 0.0550(3); 0.035, 0.037, 0.037(4); 0.027(5); 0.04(6)
Ca % : 4.93, 4.9, 4.9(4); 5.04(5); 5.08(6)
Sc ppm: 37, 36, 32(4); 36.1(5)
Ti % : 0.4, 0.4, 0.4(4); 0.38(5); 0.42(6)
V   ppm: 210, 210, 190(4)
Cr % : 0.42, 0.42, 0.41(4); 0.403(5); 0.40(6)
Mn % : 0.36, 0.36, 0.36(4); 0.363(5); 0.40(6)
Fe % : 14.9, 14.8, 14.0(4); 14.25(5); 14.72(6)
Co ppm: 48, 45, 47(4); 47.3(5); 30(6)
Ni ppm: 140, 140, 120(4); 158(5)
Zn ppm: 67, 70, 70(4); 81(5)
Ga ppm: 13(4); 12.6(5)
As ppb: 44(4); 5(5)
Se ppb: 430(4)
Br ppb: 141(5)
Rb ppm: 1.04(5)
Sr ppm: 57(5)
Ag ppb: 19(4)
Cd ppb: 37(4)
In ppb: 46(4)
Sb ppb: 10(4)
Te ppb: 5.9(4)
Cs ppb: 75(4); 75(5)
La ppm: 0.41, 0.40, 0.24(4); 0.37(5)
Ce ppm: 1.4(5)
Nd ppm: 1.4(5)
Sm ppm: 0.74, 0.70, 0.36(4); 0.75(5)
Eu ppm: 0.37, 0.36, 0.24(4); 0.35(5)
Tb ppm: 0.26, 0.24, 0.13(4); 0.30(5)
Dy ppm: 1.7(4); 2.11(5)
Ho ppm: 0.5(5)
Tm ppm: 0.11(4); 0.21(5)
Yb ppm: 1.1, 1.1, 0.56(4); 1.12(5)
Lu ppm: 0.18, 0.17, 0.09(4); 0.15(5)
Hf ppm: 0.94, 0.91, 0.90(4); 0.93(5)
Ta ppb: 30(5)
W   ppb: 83(5)
Au ppb: 3.9(4); 2.8(5)
Tl ppb: 6.9(4)
Bi ppb: 0.67(4)

EETA 79001B

Li ppm: 2.21(5)
C   ppm: 98(5); 10(6)
F   ppm: 30.9(5)
Na % : 1.20, 1.19, 1.34(4); 1.23(5); 1.25(6)
Mg % : 4.52, 4.40, 3.56(4); 4.45(5); 4.41(6)
Al % : 5.56, 5,58, 6.67(4); 5.26(5); 5.26(6)
Si % : 23(4); 22.92(5); 22.91(6)
P   % : 0.57(5); 0.55(6)
S   % : 0.192(5); 0.22(6)
Cl ppm: 48(5)
K   % : 0.081(3); 0.062, 0.062, 0.066(4); 0.054(5); 0.07(6)
Ca % : 7.43, 7.36, 7.72(4); 7.86(5); 7.86(6)
Sc ppm: 50, 49, 42(4); 50.5(5)
Ti % : 0.66,0.66, 0.78(4); 0.67(5); 0.74(6)
V   ppm: 206, 210, 180(4)
Cr % : 0.120, 0.123, 0.10(4); 0.125(5); 0.096(6)
Mn % : 0.32, 0.32, 0.31(4); 0.35(5); 0.36(6)
Fe % : 13.92, 13.84, 12.44(4); 13.79(5); 13.68(6)
Co ppm: 30, 30, 27(4); 31.1(5)
Ni ppm: 30, 30(4); 46(5)
Zn ppm: 71, 80, 80(4); 120(5)
Ga ppm: 17(4); 24.4(5)
As ppb: 21(4); 12(5)

Se   ppb: 420(4)
Br   ppb: 250(5)
Rb   ppm: 1.78(4); 1.78(5)
Sr   ppm: 67(5)
Ag   ppb: 6.3(4)
Cd   ppb: 70(4)
In   ppb: 68(4)
Sb   ppb: 16(4)
Te   ppb: 7.4(4)
I   ppm: 0.96(5)
Cs   ppm: 0.131(4); 0.131(5)
Ba   ppm: 14(5)
La   ppm: 0.81, 0.80, 0.71(4); 0.80(5)
Ce   ppm: 2.2, 2.2, 1.7(4); 3.1(5)
Nd   ppm: 3.0(4); 2.9(5)
Sm   ppm: 1.50, 1.50, 1.2(4); 1.56(5)
Eu   ppm: 0.72, 0.72, 0.60(4); 0.73(5)
Tb   ppm: 0.57, 0.50, 0.40(4); 0.64(5)
Dy   ppm: 3.7(4); 4.58(5)
Ho   ppm: 0.99(5)
Tm   ppm: 0.27(4); 0.37(5)
Yb   ppm: 2.0, 2.0, 1.4(4); 2.14(5)
Lu   ppm: 0.30, 0.30, 0.20(4); 0.30(5)
HF   ppm: 1.77, 1.7, 1.4(4); 1.93(5)
Ta   ppb: 90, 90(4); 90(5)
Au   ppb: 0.82(4); 1.1(5)
Tl   ppb: 7.9(4)
Bi   ppb: 0.76(4)

GOVERNADOR VALADARES

Na   % : 0.61(28)
Mg   % : 6.586(28)
Al   % : 0.921(28)
Si   % : 23.15(28)
K   % : 0.120(21); 0.36(28)
Ca   % : 7.0(21); 11.31(28)
Ti   % : 0.21(28)
Cr   % : 0.144(28)
Mn   % : 0.520(28)
Fe   % : 15.28(28)
Ni   ppm: 80(28)

LAFAYETTE

Na   % : 0.322(37)
Cl   ppm: 65(53)
K   % : 0.10(35); 0.094(53); 0.1(54)
Ca   % : 9.08(50); 10.1(53)
Sc   ppm: 48(37); 77.6(54)
V   ppm: 169(43)
Cr   % : 0.172(37); 0.133(50)
Mn   % : 0.386(37); 0.39(50)
Fe   % : 17.9(37); 14.84(50)
Co   ppm: 44(37); 37(50)
Ni   ppm: 106(50)
Cu   ppm: 12(37)
Zn   ppm: 71(36)
Se   ppb: 88(36)
Rb   ppm: 2.4(36)
Y   ppm: 4.4(54)
Ag   ppb: 58(36)
Cd   ppb: 92(36); 180(38)
In   ppb: 20.3(36)
Te   ppb: 140, 160(48)
I   ppb: 120, 86(48)
Cs   ppb: 288(36)
La   ppm: 1.76(54)
Ce   ppm: 5.48(54)
Pr   ppm: 0.80(54)
Nd   ppm: 3.35(54)
Sm   ppm: 0.85(54)
Eu   ppm: 0.24(54)

Gd   ppm: 0.92(54)
Tb   ppm: 0.120(54)
Dy   ppm: 0.89(54)
Ho   ppm: 0.146(54)
Er   ppm: 0.40(54)
Tm   ppm: 0.057(54)
Yb   ppm: 0.36(54)
Lu   ppm: 0.051(54)
Ir   ppb: 0.13(36)
Au   ppb: 21(36)
Tl   ppb: 7.2(36)
Bi   ppb: 5.64(36)
U   ppb: 39, 50(48)

NAKHLA

Li   ppm: 3.8(8)
B   ppm: 4.6, 255(14)
C   ppm: 696(8)
F   ppm: 57.1(8)
Na   % : 0.420(8), 0.30(27); 0.31(31); 0.377, 0.304, 0.388(37); 0.30(59)
Mg   % : 7.13(8); 7.12(27); 7.52(31); 7.24(59)
Al   % : 0.868(8); 0.83(27); 0.77(31); 0.92(59)
Si   % : 23.06(8); 22.39(27); 22.55(31); 22.89(59)
P   % : 0.045(8); 0.054(31); 0.05(40)
S   % : 0.0249(8); 0.06(59)
Cl   ppm: 1145(8); 65(53)
K   % : 0.138(8); 0.065(9); 0.03(27); 0.1075(29); 0.081(31); .0911, 0.1504, 0.1477(32); 0.0451(39); 0.109(53); 0.102(58); 0.12(59)
Ca   % : 10.22(8); 11.01(27); 10.78(31); 10.1(53); 10.84(59)
Sc   ppm: 55.0(8); 46(20); 54.5(23); 47, 53(37); 53.6(54)
Ti   % : 0.21(8); 0.18(27); 0.174(31); 0.23(59)
V   ppm: 192.4(8)
Cr   % : 0.171(8); 0.16(23); 0.16(27); 0.29(31), 0.182, 0.172(37); 0.23(59)
Mn   % : 0.426(8); 0.39(27); 0.42(31); 0.376, 0.352, 0.361(37); 0.07(59)
Fe   % : 16.87(8); 15.4(23); 14.41(27); 16.04(31); 16.4, 18.0(37); 16.16(59)
Co   ppm: 54.0(8); 48.4(23); 81(36); 43, 44, 47(37)
Ni   ppm: 90(8)
Cu   ppm: 6.7(8); 18.3(20); 5.03(36); 15, 14, 14(37)
Zn   ppm: 220(8); 64(20); 42(36)
Ga   ppm: 3.4(20); 2.70(36)
As   ppb: 15(8); 260(20)
Se   ppb: 90(20)
Br   ppm: 4.08(8); 4.37(36)
Rb   ppm: 3.15(9); 4.75(20); 3.90, 3.81, 4.74, 4.75, 3.97(29); 1.918, 1.926, 3.223, 3.247(32); 2.8(36); 2.8(51)
Sr   ppm: 51.4(9); 66.37, 56.66, 64.28, 68.23, 55.14(29); 45.20, 45.26, 73.02, 59.31(32); 60(51)
Y   ppm: 3.17(54)
Zr   ppm: 8.1(23)
Mo   ppm: 86(20)
Pd   ppb: 29, 18(16)
Ag   ppb: 40(36)
Cd   ppb: 71(36); 1790(38)
In   ppb: 24.4(36)
Sn   ppm: 0.58(20)
Sb   ppb: 6.0(8); 250(20)
Te   ppb: 110, 70(24)
I   ppb: 180(48)
Cs   ppb: 430(8); 490(20); 287(36)
Ba   ppm: 34(8); 31.3(9); 32.5(34)
La   ppm: 2.14(8); 2.28(9); 1.14(20); 2.24(34), 1.57(54)
Ce   ppm: 5.6(8); 6.20(9); 2.70(20); 5.97(34); 6.19(54)
Pr   ppm: 0.67(54)
Nd   ppm: 2.85(8); 3.552, 2.447, 4.06(9); 1.58(20); 3.11(34); 3.18(54)

Sm ppm: 0.78(8); 0.8001, 0.6195, 0.855(9); 0.50(20);
0.815(34); 0.73(54)
Eu ppm: 0.23(8); 0.276(9); 0.14(20); 0.249(34); 0.20(54)
Gd ppm: 0.840(9); 0.62(20); 0.796(34); 0.94(54)
Tb ppm: 0.13(8); 0.082(20); 0.109(54)
Dy ppm: 0.808(9); 0.52(20); 0.723(34)
Ho ppm: 0.17(8); 0.10(20); 0.14(54)
Er ppm: 0.441(9); 0.404(34); 0.34(54)
Tm ppm: 0.038(20); 0.047(54)
Yb ppm: 0.40(8); 0.397(9); 0.240(20); 0.358(34); 0.23(54)
Lu ppm: 0.062(8); 0.0577(9); 0.029(20); 0.0535(34);
0.044(54)
Hf ppm: 0.29(8); 0.25(23)
Ta ppb: 90(8)
W ppb: 176(8)
Re ppb: 0.09(42)
Os ppb: 1(20); 0.7(41)
Ir ppb: 0.3(20); 17(36)
Au ppb: 2.9(8); 0.7(20); 0.55(36)
Hg ppb: 0.7(20); 2.5(44); 230(49)
Tl ppb: 3.1(36)
Pb ppb: 509(9)
Bi ppb: 0.50(36)
Th ppb: 236(9); 191, 190(52)
U ppb: 55.9(9); 40(48); 47.8, 50.7(52)

SHERGOTTY

Li ppm: 3.3(2); 3.94, 4.20, 5.06, 5.59(7); 5.6(8); 4.1(10)
C ppm: 430(2); 620(8)
F ppm: 41(2); 41.6(8)
Na % : 1.04, 1.09, 0.96, 0.95(2); 0.957(8); 1.02,
0.96(19); 1.27, 0.93, 1.34(37); 0.936, 0.97(45);
0.95(47)
Mg % : 5.73, 5.40, 5.43(2); 5.60(8); 5.59(19); 5.59(31);
5.64(45); 5.67(47)
Al % : 3.78, 4.02, 3.60(2); 3.74(8); 3.65(19); 3.72(31);
3.04(45); 3.54(47)
Si % : 23.14(2); 24.01(8); 23.6(19); 23.54(31);
24.07(45); 23.42(47)
P % : 0.31(2); 0.35(8); 0.204(31); 0.31(47)
S % : 0.157(2); 0.133(8)
Cl ppm: 108(2); 108(8)
K % : 0.158, 0.157, 0.1024, 0.1510(1); 0.16, 0.157,
0.12, 0.137(2); 0.13(3); 0.136(8); 0.139(10);
0.13(15); 0.13(19); 0.149(31); 0.108(45);
0.13(47); 0.151(57)
Ca % : 6.81, 6.88, 6.95, 7.06(2); 7.15(8); 6.0(15);
7.22(19); 6.85(31); 7.33(45); 7.17(47)
Sc ppm: 54.0, 53.8, 56.5, 57.8(2); 58.9(8); 53(19); 49, 35,
26(37); 48, 50.3(45)
Ti % : 0.5, 0.4, 0.52(2); 0.52(8); 0.49(19); 0.512(31);
0.55(47)
V ppm: 260, 265(2); 380(45)
Cr % : 0.123, 0.137, 0.132, 0.125(2); 0.139(8); 0.14,
0.15(19); 0.21(31); 0.035(37); 0.15, 0.14(45);
0.12(47)
Mn % : 0.403, 0.401, 0.414, 0.418(2); 0.403(8); 0.39(19);
0.417(31); 0.41, 0.154(37); 0.38, 0.387(45);
0.39(47)
Fe % : 15.24, 15.40, 15.47, 15.63(2); 15.09(8); 14.85,
14.23(19); 15.03(31); 12.6, 11.0(37); 15.40,
14.24(45); 15.54(47)
Co ppm: 37.5, 37.9, 37.2, 38.5, 39.5, 37.2(2); 38(4); 39(8);
35(19); 63(36); 1150, 62, 910(37); 37,
39.5(45)
Ni ppm: 70, 81, 70, 88(2); 83(8); 56(19); 80(25); 81(45)
Cu ppm: 26(2); 26(8); 11.9(36); 139(37); 11(45)
Zn ppm: 67, 69.8, 68, 68.4(2); 76(4); 83(8); 54(25); 76(36)
Ga ppm: 17.5, 17.6, 15.7, 16.5(2); 15(4); 14.7(8);
16.7(25); 13.9(36)
Ge ppb: 770(25)
As ppb: 25(2); 25(8)

Se ppb: 380, 400(2); 470(4); 410(8); 242(36)
Br ppb: 890, 800(2); 600(8); 1070(36)
Rb ppm: 6.61, 6.81, 6.04, 7.53(1); 7.27, 6.11(2); 6.84(8);
6.22(10); 5.85, 5.70, 6.19(18); 6.1(36)
Sr ppm: 45, 54(2); 51(8); 51.0(10); 42.6, 34.4, 50.7(18);
35(45)
Y ppm: 19(47)
Zr ppm: 67, 50(2); 41(47)
Nb ppm: 22(47)
Mo ppb: 370(2)
Ag ppb: 10.5, 6.8(2); 110(4); 263(36)
Cd ppb: 44, 14(2); 340(4); 23(25); 44(36)
In ppb: 25, 23(2); 23(4); 23(25); 31.3(36)
Sn ppm: 11(47)
Sb ppb: 8.9(2); 27(4)
Te ppb: 19, 4.3(2); 3.2(4)
I ppb: 36(2); 50(8)
Cs ppb: 460, 480, 400, 420(2); 440(4); 405(8); 380(36)
Ba ppm: 32.0, 37.0, 40, 39(2); 35.5(8); 29.4(10); 40(45);
32(46); 6(47)
La ppm: 2.33, 2.44, 1.90, 1.97(2); 2.29(8); 1.50(10);
2.18(19); 1.93(45)
Ce ppm: 6.7, 6.4, 5.1, 5.6(2); 5.54(8); 3.51(10); 5.89(46)
Pr ppm: 1.0, 0.82(2); 0.86(8)
Nd ppm: 4.221(1); 4.8, 4.7, 4.1, 4.3(2); 4.5(8); 2.632,
2.460, 2.60(10); 4.96(46)
Sm ppm: 1.630(1); 1.60, 1.66, 1.30, 1.46(2); 1.37(8); 1.01,
1.009, 0.9724(10); 1.36(19); 1.37(45);
1.89(46)
Eu ppm: 0.63, 0.65, 0.55, 0.55(2); 0.564(8); 0.430(10);
0.53(19); 0.55(45); 0.643(46)
Gd ppm: 2.5, 2.8, 2.1, 2.5(2); 2.2(8); 1.64(10); 2.80(46)
Tb ppm: 0.52, 0.52, 0.41, 0.41(2); 0.44(8)
Dy ppm: 4.3, 4.8, 3.4, 3.1(2); 2.94(8); 2.16(10); 3.38(46)
Ho ppm: 0.89, 0.86, 0.75, 0.80(2); 0.56(8)
Er ppm: 1.87(8); 1.33(10); 1.89(46)
Tm ppm: 0.32, 0.31, 0.27, 0.30(2); 0.38(8)
Yb ppm: 1.80, 1.79, 1.50, 1.62(2); 1.69(8); 1.19(10);
1.59(19); 1.40(45); 1.80(46)
Lu ppm: 0.26, 0.26, 0.22, 0.24(2); 0.25(8); 0.176(10);
0.26(19); 0.34(45)
Hf ppm: 2.15, 2.23, 1.50, 1.83(2); 1.97(8); 2.0(10);
2.0(19); 2.15(45)
Ta ppb: 290, 270, 180, 230(2); 250(8); 270(10); 270(19)
W ppb: 500, 400(2); 480(8)
Ir ppb: 0.4(5); 0.072(25); 1.55(36)
Au ppb: 5.4, 0.9, 0.81, 6(2); 12(4); 8(5); 16(8); 0.98(25);
88(36)
Tl ppb: 14.0, 0.15(2); 11(4); 13.4(36)
Bi ppb: 1.2, 0.47(2); 1.6(4); 3.7(36)
Th ppb: 370, 370, 250, 290(2); 390(8); 350(10); 350(19);
471, 461(33)
U ppb: 95, 120, 95, 55, 95, 95(2); 171(4); 116(8); 105,
120(33)

ZAGAMI

Li ppm: 3.82(10)
Na % : 0.898(4); 0.73, 0.85(19); 0.9(22)
Mg % : 6.70(4); 6.63(19); 6.88(22)
Al % : 3.4(4); 3.00(19); 3.02(22)
Si % : 23(4); 23.75(19); 23.80(22)
P % : 0.21(22)
K % : 0.116(3); 0.12(4); 0.1243(10); 0.12(19); 0.08(22)
Ca % : 7.58(4); 7.72(19); 7.51(22)
Sc ppm: 53(4); 57(19)
Ti % : 0.5(4); 0.46(19); 0.44(22)
V ppm: 312(4)
Cr % : 0.20(4); 0.21, 0.235(19); 0.26(22)
Mn % : 0.39(4); 0.39(19); 0.39(22)
Fe % : 14.8(4); 14.00, 14.00(19); 13.74(22)
Co ppm: 36(4); 37(19)

Ni	ppm:	50(4); 67(19); 140(22)
Zn	ppm:	62(4); 55(36)
Ga	ppm:	14(4)
As	ppb:	46(4)
Se	ppb:	320(4); 330(36)
Rb	ppm:	5.7(4); 5.69, 5.09, 5.56(10); 6.0(36)
Sr	ppm:	46(4); 45.9, 42.8, 46.5(10)
Ag	ppb:	31(4); 37(36)
Cd	ppb:	61(4); 71(36)
In	ppb:	22(4); 22.2(36)
Sb	ppb:	12(4)
Te	ppb:	1.0(4)
Cs	ppb:	380(4); 336(36)
Ba	ppm:	25(4)
La	ppm:	0.90(4); 1.6(10); 2.07(19)
Ce	ppm:	3.75(10)
Nd	ppm:	2.89, 2.381, 4.078, 2.983(10)
Sm	ppm:	0.76(4); 1.17, 0.993, 1.639, 1.215(10); 1.42(19)
Eu	ppm:	0.44(4); 0.476(10); 0.51(19)
Tb	ppm:	0.22(4); 0.34(19)
Dy	ppm:	1.74(4); 2.66(10)
Er	ppm:	1.60(10)
Yb	ppm:	0.98(4); 1.38(10); 1.45(19)
Lu	ppm:	0.13(4); 0.201(10); 0.255(19)
Hf	ppm:	1.7(4); 1.9(19)
Ta	ppb:	200(4); 220(19)
Ir	ppb:	0.10(36)
Au	ppb:	2.2(4); 2.10(36)
Tl	ppb:	12(4); 11.0(36)
Bi	ppb:	5.1(4); 1.1(36)
Th	ppb:	270(19)
U	ppb:	154(4)

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