

THE EARTH CONTAINS A LARGE FRACTION OF MATERIAL NOT REPRESENTED BY METEORITES. H. Palme and J. Zipfel. Senckenberg, Naturmuseum und Forschungsinstitu, Senckenberganlage 25, 60325 Frankfurt, Germany, e-mail: palmeherbert@gmail.com

Chondritic meteorites have approximately the chemical composition of the photosphere of the Sun for non-gaseous elements. This implies roughly the same number of Mg, Si and Fe atoms, and about ten times fewer Al and Ca atoms. One group of meteorites, the CI-chondrites has element abundances identical to the solar photospheric abundances to within 10% for most elements [1,2]. Other groups of chondritic meteorites deviate in their abundance patterns somewhat from the solar composition. This is demonstrated in Fig. 1, which shows the Si-normalized Mg, Al and Mn abundances in the most common groups of chondritic meteorites. Thus two major categories of chondritic meteorites can be distinguished: (1) Non-carbonaceous chondrites (NCC) including enstatite chondrites, ordinary chondrites, and Rumurutiites and (2) carbonaceous chondrites (CC). Both categories show characteristic differences in bulk chemistry and in stable isotope composition, suggesting different environments of formation (see [3] for sources of data).

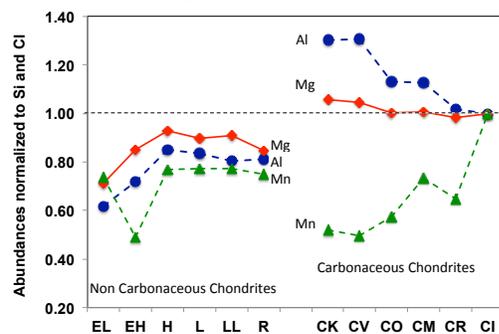


Fig. 1: Al/Si, Mg/Si and Mn/Si in Non Carbonaceous Chondrites (NCC) and in Carbonaceous Chondrites (CC).

All data in Fig. 1 are normalized to Si and CI-chondrites. All NCC groups are depleted in Mg and Al, CC have solar Mg/Si ratios but are variably enriched in Al and other refractory elements. There is no transition between the two categories. The moderately volatile element Mn is depleted in all NCC to a similar extent as Mg whereas CC, except CI, show larger depletions.

Al represents refractory elements. Until recently ratios among refractory elements were assumed to be identical in all chondritic meteorites. It appears now that there are small but distinctive differences in some refractory lithophile and siderophile element ratios between NCC and CC. NCC have small but measurable Tm deficits, whereas CC have unfractionated REE or small Tm-excesses [5, 6]. The Y/Ho ratios seem to be lower in CC than in OC and EC. Similarly carbona-

ceous chondrites have 8% lower Re/Os ratios than NCC [7]. This difference was probably established early in the solar system history as inferred from Os-isotope ratios. There may be more subtle difference in refractory element ratios between CC and NCC, but they are difficult to measure as elements need to be determined in a single sample and with high accuracy. Besides chemical differences there are differences in stable isotopes between NCC and CC. From recent data on stable isotopes, summarized by [8] one can see the dichotomy between NCC and CC. The abundances of neutron-rich isotopes ^{50}Ti , ^{54}Cr , ^{62}Ni are all higher in CC [9]. In a three isotope plot $\Delta^{17}\text{O}$ values of CC are negative and those of NCC positive [10]. Characteristic differences between CC and NCC are found in Mo-[11] and Ba-isotopes [12]. NCC are characterized by neutron-rich isotopes and a higher proportion of r-process nuclei. Primitive achondrites and differentiated meteorites seem to have in most cases the stable isotope ratios of NCC (e.g., Acapulcoites, HEDs), except for oxygen isotopes.

The NCC groups in Fig. 1 are arranged according to increasing oxygen contents from left to right and the CC are arranged with decreasing Al/Si. Attempts have been made to transform the sequence of chondrite classes (Fig. 1) into a radial distance of formation from the Sun [13], NCC in the inner solar system within the range of terrestrial planets and CC further out beyond the waterline, in the asteroid region. The sequence of chondritic meteorite plotted in Figs. 1,2 would thus correspond to increasing radial distance from the Sun. In both categories, CC and NCC, oxygen and $\Delta^{17}\text{O}$ increases from left to right (Fig.1). In CC this may indicate an increase in water. For NCC this is unlikely. The high oxygen content of R chondrites is not the result of higher water content. There are barely hydrous phases in primitive oxygen-rich R chondrites [14]. It appears that for the inner solar system increasing oxygen does not necessarily mean increase in water.

How does Earth fit into this sequence? Because of the apparent similarity of stable isotopes of Earth with NCC, Earth's mantle is plotted with NCC in Fig. 2, although its high Al/Si and Mg/Si ratios show similarities with CC as does its low Mn and other volatiles [3]. The Mg and Al points of BSE in Fig. 2 are plotted by assuming no Si in Earth's core, emphasizing the well known Si deficit in the Earth's mantle ([15,3] and references). Assuming 8-9% Si in the core [16] would reduce the Al/Si of bulk Earth to the CV-level, which is still excessive compared to NCC (Fig. 2). This interpretation has been challenged by [17] and the authors

assume that present BSE Mg/Si ratio is identical to that of bulk Earth. This argument is based on a correlation of ^{30}Si with Mg/Si for chondritic meteorites [17].

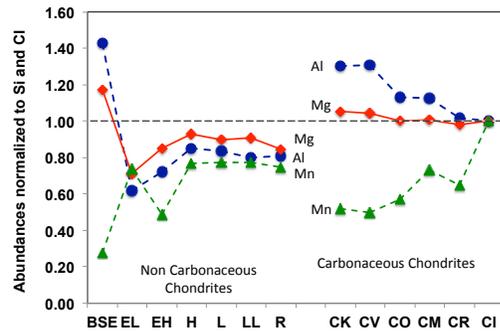


Fig. 2: As Fig. 1, but with the addition of Earth's mantle (BSE) [3].

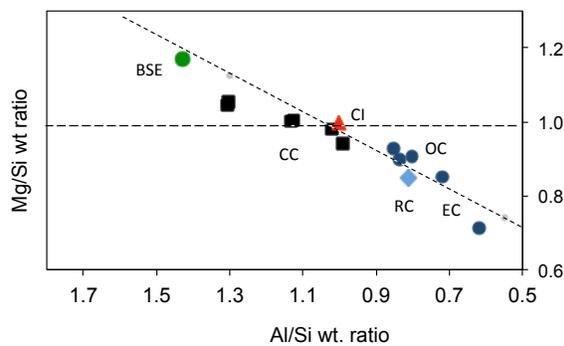


Fig. 3: Mg/Si vs Al/Si in chondrites and the Earth. Earth's core is assumed to be free of Si.

In Fig 3, Mg/Si is plotted vs Al/Si together with the results of a least squares fit based only on NCC, because of stable isotope similarities between Earth and NCC. BSE is assumed to represent bulk Earth. The high Al/Si and Mg/Si of Earth is clearly visible. Assuming that this composition contains a certain fraction of NCC material, Earth must have components higher in Mg/Si and Al/Si than bulk Earth to balance the low Mg/Si and Al/Si ratios of NCC (Figs. 2,3). The required fraction of unknown material high in Mg and Al may be up to 90 % depending on the fraction of NCC. Addition of CV-material to bulk Earth is limited by stable isotopes. In Mo-isotopes the Earth has an endmember composition. A substantial fraction Mo with opposite isotopic signatures not recorded in existing meteorites has to be added to existing meteorites to arrive at a bulk Earth isotopic Mo composition [11].

The Earth cannot be produced by any combination of CC or NCC, neither with respect to chemical composition nor stable isotopes. A large fraction of bulk Earth must be higher in Mg and refractory elements

and lower in Mn and other volatile elements than known chondritic meteorites.

Massive fractionations of a solar-like nebula are required to produce the parental material of the Earth. These fractionations are caused by enrichment in early condensing Ca, Al-rich material and forsterite and a strong depletion of volatiles. Refractory element enrichment may be accompanied by some fractionation, e.g., the Tm-anomaly. The volatile element depletion must be an early event considering the very low $^{53}\text{Cr}/^{52}\text{Cr}$ of bulk Earth [19]. If compared to existing chondrites, Earth is in a strict sense non-chondritic [20]. In a broader sense the bulk Earth composition may still be considered chondritic, as its major element composition can be extrapolated from existing chondrite trends (Fig. 3).

In [18] a hypothetical Angrite parent body (APB) is involved in the bulk Earth composition, as it fits with some stable isotopes and low volatiles. But we have only highly fractionated samples from the APB, extrapolation to the bulk APB are speculative and the major element composition of APB is unknown.

Summary:

There are two categories of chondritic meteorites NCC and CC. Based on stable isotopes bulk Earth can only have a small fraction of CC. The amount of NCC component is limited by low Al, high Si and high Mn of NCC (Figs. 2,3). Although bulk Earth may be considered in a broad sense chondritic, only a small fraction of parental material can be derived from existing meteorites.

Lit.: [1] Lodders et al. (2009) In: Trümper JE (ed.) Landolt-Börnstein, New Series, VI/4B, pp. 560–598. [2] Asplund M. et al. (2009) Annual Review of Astronomy and Astrophysics 47: 481–522. [3] Palme H. & O'Neill H.St.C. (2014) In: Holland H.D. & Turekian K.K. (eds.) Treatise on Geochemistry, Second Edition, vol. 3, pp. 1-39, Elsevier. [5] Dauphas N. & Pourmand A. (2015) *GCA* 163, 234-261. [6] Barrat J.A. et al. (2016) *GCA* 176, 1-17. [7] Horan M.F. et al. (2003) *Chemical Geology* 196, 5-20. [8] Warren P. (2011) *EPSL* 311, 93-100. [9] Zhang J. et al. (2012) *Nature Geoscience* 5, 251-255. [10] Clayton R.N. (1993) *Ann. Rev. Earth Planet. Sci.* 21, 115-149. [11] Burkhardt C. et al. (2011) *EPSL*, 312, 390-400. [12] Andreasen R. & Sharma M. (2007) *Astrophysical Journal* 665, 874–883. [13] Rubin A.E. (2011) *Icarus* 213, 547-558. [14] Bischoff A. et al. (2011) *Chemie der Erde* 71, 101-133. [15] Fitoussi et al. (2009) *EPSL* 287, 77-85. [16] Rubie D.C. et al. (2015) *Icarus* 248, 89-108. [17] Dauphas N. et al. (2015) *EPSL* 427, 236-248. [18] Fitoussi et al. (2016) *EPSL* 434, 151-160. [19] Campbell I.H. & O'Neill H.St.C. (2012) *Nature* 483, 553-558. [20] Palme H. & Kleine T. (2012) *43rd LPSC*, #2163.