

MAKING EARTH FROM CHONDRITIC COMPONENTS, NOT CHONDRITES. C. M. O'D. Alexander and K. Shimizu. DTM, Carnegie Institution for Science, Washington, DC 20015, USA (calexander@carnegiescience.edu).

Introduction: Chondrites are fragments of asteroids that accreted roughly 2-4 Ma after formation of the Solar System. It was also at about this time that at least some Mars-sized embryos were growing [1]. These embryos were the main building blocks during the final stages in the formation of Earth and Venus. Unlike earlier formed planetesimals, the chondrite parent bodies did not undergo widespread melting and they preserve in their physical characteristics and compositions 'memories' of the processes operating in the nebula during the early stages of terrestrial planet formation.

It has been common to try to build the terrestrial planets from bulk chondrites. However, it seems likely that most of the planetesimal building blocks of the terrestrial planets formed before the chondrites and/or in different regions of the nebula. If correct, then the chondrites are not likely to be close analogs. This conclusion is supported by the differing elemental and isotopic characteristics of the chondrites and Earth.

Recently, it has become common to refer to chondrites as being either carbonaceous (CC) or non-carbonaceous (non-CC) chondrites due to an apparent dichotomy in their bulk isotope anomalies that has been attributed to their formation in the inner (non-CC) from the outer (CC) Solar System [2].

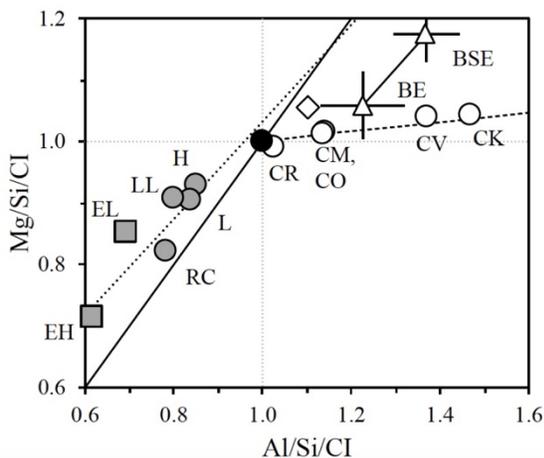


Fig. 1. The Si- and CI-normalized compositions of the major chondrite groups [3, 4], and estimates for the bulk Earth (BE) and bulk silicate Earth (BSE) [5]. The CC trend is due to addition of refractory inclusions. The non-CCs lost material that was less refractory than the inclusions added to the CCs.

It has been known for decades that the CCs and non-CCs fall on two distinct trends in plots of bulk Mg/Si vs. Al/Si (Fig. 1). In Fig. 1, the CCs form an Al and Mg enrichment trend, relative to Si, that is consistent with the addition of refractory inclusions to CI-like material,

which can also explain much of the isotopic variations amongst the CCs [4]. On the other hand, the non-CCs form an Al and Mg depletion trend, relative to Si, that requires the loss of a less refractory material (i.e., lower Al/Si) than was added to the CCs. Another striking difference between the CC and non-CCs is in the behavior of their moderately volatile elements [e.g., 3, 4]. The moderately volatile elements in the CCs generally exhibit a smooth decrease in abundance with decreasing condensation temperature irrespective of their chemical affinities. On the other hand, in the non-CCs the moderately volatile lithophiles exhibit no clear trend with condensation temperature. The moderately volatile siderophiles in the OCs and RCs do show some evidence of volatility control, but variable metal/silicate fractionation was almost as important in determining the diversity of their compositions. The ECs do not display any systematic behavior with condensation temperature.

Since the Earth formed in the inner Solar System, it is not surprising that isotopically it more closely resembles the non-CCs than the CCs. Indeed, the bulk silicate Earth (BSE) is almost identical isotopically to the ECs, leading many to suggest that the building blocks of the Earth were dominated by compositionally EC-like objects. However, estimates of the BSE's elemental composition more closely resemble those of the CCs [e.g., 5, 6] (Fig. 1). Earth's mixed elemental and isotopic affinities means that no chondrite-based model can satisfy both sets of constraints.

On the other hand, all chondrites are built from the same three basic components. It seems likely that this was also true for Earth's major building blocks. Although the three components seem to be the products of fundamental nebula-wide processes, the variations in their physical/chemical/isotopic properties show that their formation conditions varied with time/place in the nebula. Here we explore what component compositions best reproduce the Earth's composition.

Model outline: The dominant component is composed of type I chondrules whose volatile element depletions closely mimic those of the BSE [7]. The type I composition used here is the average CC chondrule composition of [4]. This composition has had some metal depletion, so it was necessary to add back metal to reproduce the BE composition. To explain the Al-rich composition of the BE (Fig. 1) it is necessary to add refractory inclusion material. However, to reproduce the best estimate for the BE, the refractory component must be more Mg- and Si-rich (more AOAs) than that added to the CCs. The most volatile elements (e.g., H, C, N and noble gases), are accreted in predominantly in CI-like material, accompanied by a small amount of

implanted solar wind and synthetic comet material. The cometary material was assumed to be composed of equal parts ice [8], refractory organics and volatile-free CI-like silicates. The bulk composition of the organics is based on the composition of primitive IOM with bulk CI noble gas abundances scaled to pure IOM. Finally, there is a late veneer composed of EH material, although similar results are obtained with other non-CC groups.

Results and Discussion:

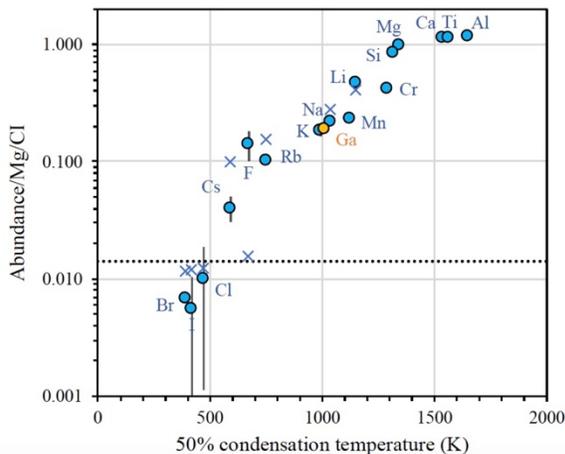


Fig. 2. Comparison of BSE lithophile element, as well as nominally siderophile Ga, abundances (circles) with model results (crosses). Only model results where there is significant disagreement are shown. Condensation temperatures are from [9].

The model is able to reproduce the abundances of almost all elements in the BSE. For many elements, this is because there are few if any constraints on how much of them can partition into the core. However, for some lithophiles this is not the case. Fig. 2 shows those elements (crosses) for which there is a significant difference between the model and the BSE of [5]. For several lithophiles it was still necessary to put some fraction in the core (Si–9.5%, Mn–39%, Cr–48%, Ga–16%). The total amount of light elements in the model core is 8.7 wt.%. For those elements not allowed to partition into the core, the abundances of Rb and Cs are significantly overestimated by the model, while F is considerably underestimated. The abundances of Br and I are overestimated, but their BSE abundances are very uncertain.

The amount of CI, cometary and implanted solar wind added in the model was constrained by the BSE Ne, Ar and Kr abundances [10, 11], as well as the Ne isotopic composition of the atmosphere. Fig. 3 compares the model results with BSE estimates for a number of the most volatile elements. The large depletion in BSE Xe is due to gradual loss from the atmosphere [12]. The significant depletions in N and, possibly, C have been attributed to impact loss of an early degassed

atmosphere(s) [13]. However, the solubilities of N₂ and CO₂ in silicate melts are similar to undepleted Ar and Ne, respectively, and should degas from a magma ocean to similar degrees. If correct, it seems likely that there are hidden reservoirs of N and, possibly, C in the deep Earth.

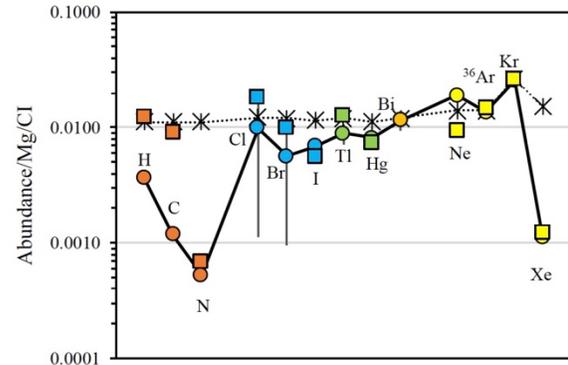


Fig. 3. Comparison of two pairs of estimated BSE abundances of the most volatile elements (circles - [5, 11]; Squares - [6, 10]) with the model results (stars).

Isotopes can also provide important constraints on the model. The isotopic compositions of the Ru and Os will be dominated by the late veneer, in this case EH material. The mixed CC and non-CC composition of BSE Mo [14] can be explained if the CI material was accreted towards the end of core formation. The sizes of the model type I chondrule ⁴⁸Ca, ⁵⁰Ti, and ⁵⁴Cr anomalies required to reproduce the BSE compositions largely depend on the mass fraction of refractory inclusions needed to reproduce the BE composition, and in the case of ⁵⁴Cr whether the inclusions were accompanied by ⁵⁴Cr-depleted material as in the CCs [4]. For the BE composition used here, the anomalies in these elements lie beyond those for any known non-CC materials. However, at lower Al contents allowed by the BE uncertainties the anomalies approach those of the ureilites.

References: [1] Tang H. and Dauphas N. (2014) *EPSL* 390, 264-274. [2] Warren P.H. (2011) *EPSL* 311, 93-100. [3] Alexander C.M.O'D. (2019) *GCA* 254, 246-276. [4] Alexander C.M.O'D. (2019) *GCA* 254, 277-309. [5] Wang H.S. et al. (2018) *Icarus* 299, 460-474. [6] Palme H. and O'Neill H.S.C. (2014) in *Treatise on Geochemistry*, vol.3, p. 1-39. [7] Hewins R.H. and Herzberg C.T. (1996) *EPSL* 144, 1-8. [8] Rubin M. et al. (2018) *Sci. Adv.*, 4, eaar6297. [9] Wood B.J. et al. (2019) *Amer. Mineral.* 104, 844-856. [10] Marty B. (2012) *EPSL* 313-314, 56-66. [11] Dauphas N. and Morbidelli A. (2014) in *Treatise on Geochemistry*, vol. 6, p. 1-35. [12] Avicé G. et al. (2018) *GCA* 232, 82-100. [13] Tucker J.M. and Mukhopadhyay S. (2014) *EPSL* 393, 254-265. [14] Budde G. et al. (2019) *Nat. Astron.* DOI:10.1038/s41550-019-0779-y.