DETERMINING POSSIBLE BUILDING BLOCKS OF THE EARTH.

T. H. Burbine[1] and K. M. O'Brien[2], [1]Goddard Space Flight Center, Laboratory for Extraterrestrial Physics, Code 691, Greenbelt, MD 20771, USA (thb@alum.mit.edu), [2]11152 Wallingsford Road, Los Alamitos, CA 90720, USA (kobrien@socal.rr.com).

Introduction: One of the fundamental questions concerning the formation of the Earth is what is it made out of. The Earth appears to have condensed out of material from the solar nebula. We sample this "primitive" material in the form of chondritic meteorites. One of the most important constraints on possible building blocks for the Earth is the Earth's oxygen isotopic composition. Rocks from the Earth and Moon plot along a line (the terrestrial fractionation line) in diagrams of δ^{17}O (‰ relative to Standard Mean Ocean Water or SMOW) versus δ^{18}O (‰ relative to SMOW). Chondritic meteorites fall above and below this line. Distances from this line are given as Δ^{17}O (‰) (= δ^{17}O - 0.52 x δ^{18}O).

Recently, Drake and Righter [1] argued that the primary building blocks of Earth are some type of "Earth chondrite" or "Earth achondrite" that is not currently found in our meteorite collections. They use as evidence the fact that in a plot (Figure 1) of weight ratios of Mg/Si versus Al/Si, the trend for terrestrial rocks plots distinctly away from the trend for chondritic meteorites. The trend for differentiated terrestrial rocks (peridotites, komatiites, basalts) is due to magmatic fractionation (differentiation).

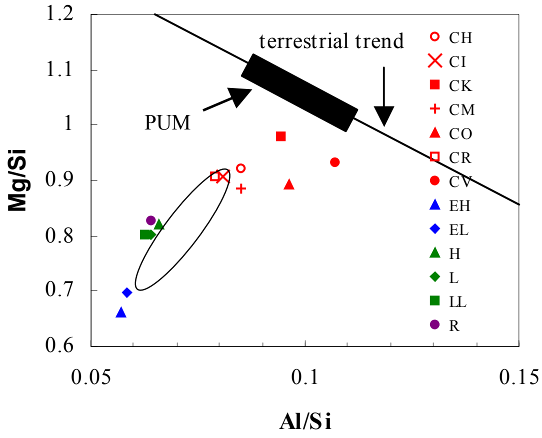

Figure 1. Plot of Mg/Si versus Al/Si for the chondritic meteorites (average values). The line is the trend for terrestrial rocks estimated from Dreibus et al. [2]. The ellipse is the approximate distribution of matches with Δ^{17}O values within ±0.01‰ of the terrestrial fractionation line and Fe/Al weight ratios of 20 ± 2. The black box shows the approximate region where estimates of the primitive upper mantle (PUM) tend to fall.

The composition of the primitive upper mantle (PUM) appears depleted in Si relative to the chondritic meteorites. Possible solutions to this "Si-deficit problem" include sequestering Si in the core and/or the lower mantle. Putting significant amounts of Si in the core requires differentiation under very reducing conditions, similar to those found in aubrites.

A number of researchers [3,4] believe that one of the best-known compositional characteristics of the bulk Earth is the Fe/Al ratio, which they estimate as 20 ± 2. This Fe/Al ratio is derived by assuming that there is no Al in the core, the core is 85 wt.% Fe, and we can accurately estimate the aluminum content of the PUM from peridotite samples.

To determine what material could possibly be the building blocks of the Earth, we have looked at hundreds of millions of possible combinations of different types of chondritic material to try to match the Earth's oxygen isotopic composition. We then try to find combinations that match the Earth's estimated Fe/Al ratio of 20 ± 2 and come closest to the Earth's bulk Al/Si and Mg/Si weight ratios.

Program: The program first checks for all possible combinations of meteorites that had Δ^{17}O values within +0.01‰ of the terrestrial fractionation line since this is the most concrete constraint on possible building blocks of the Earth. We then check for all possible combinations of meteorites that had Δ^{17}O values within ±0.01‰ of the terrestrial fractionation line and that also have Fe/Al weight ratios of 20 ± 2.

The program takes as input the values of Δ^{17}O (‰), Si (wt.%), Al (wt.%), Mg (wt.%), and Fe (wt.%) for each meteorite type. We assume that none of these elements are lost during the formation of the Earth and homogeneous accretion. The program then generates all possible combinations of meteorite percentages, at a user-specifiable increment (in this case 5%) that equal a total of 100%.

For each combination, the aggregate value of Δ^{17}O (‰), Si (wt.%), Al (wt.%), Mg (wt.%), Fe (wt.%), Mg/Si, Al/Si, and Fe/Al are computed. The values of the aggregate Δ^{17}O (‰) and Fe/Al ratios are checked against given respective tolerances. If the values are within the tolerances (called a "match"), the results are noted and/or stored, and several counters are incremented. We also saved the 1000 matches that were closest to the terrestrial line in Mg/Si-Al/Si space.

Results (within ±0.01‰ of the terrestrial fractionation line): Using increments of 5%, there were

225,792,840 possible combinations. There were 1,261,860 matching combinations (0.56% of the total) within ±0.01‰ of the terrestrial fractionation line. The meteorites whose $\Delta^{17}O$ (‰) values were closest to the terrestrial fractionation line tended to have the highest percentages. There are a huge number of possible combinations that fit the criteria of being within ±0.01‰ of the terrestrial fractionation line.

For the matching combinations within ±0.01‰ of the terrestrial fractionation line, we looked at the top 100 matches to the terrestrial line in Mg/Si-Al/Si space. Since all of the chondritic meteorites fall below this line, obviously none of the matches can intersect it. Interestingly, the top matches to the line are heavily dominated by CI chondritic material and plot near the CI chondrites in Figure 1. This is due to the CI chondrites being the best match among the chondrites to the bulk Earth in $\Delta^{17}O$ (‰) and in weight ratios of Mg/Si, Al/Si, and Fe/Al. Enstatite chondrites are better matches to the bulk Earth in $\Delta^{17}O$ (‰), but differ considerably in composition. CK, CO, and CV chondrites are closer in composition, but differ significantly in average $\Delta^{17}O$ (‰). For the best match to intersect the terrestrial line in Mg/Si-Al/Si space, the amount of Si must be reduced by 15% and for the 100th best match, there must be a reduction of 17%.

Results (within ±0.01‰ of the terrestrial fractionation line and with a Fe/Al of 20 ± 2): There were 637,739 matching combinations (0.28% of the total) within ±0.01‰ of the terrestrial fractionation line and with a Fe/Al ratio of 20 ± 2. The approximate distribution of these points is plotted in Figure 1. The CI chondrites have the largest possible mixing percentage (90%) with the EL and ordinary (H, L, LL) chondrites having slightly smaller percentages. CH chondrites have the lowest possible percentage (20%) due to their extremely high Fe/Al value. There are a huge number of possible combinations that fit the criteria of being within ±0.01‰ of the terrestrial fractionation line and have a Fe/Al value of 20 ± 2. Matches with 50% or more of a particular meteorite type occur for CI, CR, EL, H, L, LL, and R chondrites.

We looked at the best matches to the terrestrial line in Mg/Si-Al/Si space. The best matches are also heavily enriched in CI material. For the best match to intersect the terrestrial line in Mg/Si-Al/Si space, the amount of Si must be reduced by 15%.

Conclusions: Our rigorous modeling using hundreds of millions of possible combinations of chondritic material confirms what many other researchers have recognized previously: the best compositional matches to the Earth tend to be dominated by CI chondritic material since the CI chondrites are the best match among chondritic meteorites to the Earth both in $\Delta^{17}O$ (‰) and in weight ratios of Mg/Si, Al/Si, and Fe/Al. However, the resulting Mg/Si and Al/Si ratios of CI-dominated material fall away from the Mg/Si-Al/Si trend for the Earth. Computer modeling shows that the best matches need to remove at least 15% of the silicon to match the trend for the Earth.

There are a myriad of combinations of chondritic meteorites that are not dominated by CI material that fall on the terrestrial fractionation line and have Fe/Al ratios of 20 ± 2. These matches fall farther from the Mg/Si-Al/Si trend for the Earth than matches dominated by CI chondrites and have larger Si deficits.

It appears unlikely that all of the Si could be in the core. Assuming the bulk Earth contains 17.2 wt.% Si [4], a 15% loss of Si corresponds to ~8 wt.% Si in the core. Horse Creek, an anomalous iron-rich meteorite that formed under very reducing conditions, contains metal with only 2-3 wt.% Si [5].

The basic subdivision of the Earth according to seismic properties is an upper mantle (down to a depth of ~410 km), a transition zone (~410-660 km), and a lower mantle (~660-2890 km) [6]. We only sample the upper mantle and can only guess at the composition of the rest of the mantle by using seismic studies and laboratory experiments. Steep density gradients, generally believed to be due to high-pressure phase changes of silicate minerals, define the boundaries of the transition zone. What is unclear is if there are also compositional differences at these discontinuities.

Another possibility is that the Earth primarily formed out of some unknown type of "Earth chondrite" or "achondrite" material that matches the oxygen isotopic composition of the Earth and has Al/Si and Mg/Si ratios similar to the PUM. However, unless such a sample is found, this type of scenario is impossible to prove or disprove.

Future Work: We are currently using this technique to determine possible building blocks of Mars. By investigating another body, we hope to better constrain scenarios for building the inner planets.

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