DETERMINING POSSIBLE BUILDING BLOCKS OF THE EARTH AND MARS. T. H. Burbine[1] and K. M. O'Brien[2], [1]Laboratory for Extraterrestrial Physics, Code 691, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (tburbine@lepvax.gsfc.nasa.gov), [2]1152 Wallingsford Road, Los Alamitos, CA 90720 USA (ko-brien@socal.rr.com).

Introduction: One of the fundamental questions concerning planetary formation is exactly what material did the planets form from? All the planets in our solar system are believed to have formed out of material from the solar nebula. Chondritic meteorites appear to sample this primitive material. Chondritic meteorites are generally classified into 13 major groups, which have a variety of compositions.

Detailed studies of possible building blocks of the terrestrial planets require samples that can be used to estimate the bulk chemistry of these bodies. This study will focus on trying to determine possible building blocks of Earth and Mars since samples of these two planets can be studied in detail in the laboratory.

Program: The program takes as input the total number of chondritic meteorite types and the values of ^{17}O (‰), ^{17}O (‰), and ^{18}O (‰) plus weight percents of O, Si, Al, Mg, Fe, FeO, Fe_2O_3, Fe_3O_4, Fe (metal), C, and H_2O for each meteorite type. 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%. The total number of combinations at 5% mass increments is over 225 million.

For each combination, the aggregate values of ^{17}O (‰), ^{17}O (‰), and ^{18}O (‰) plus weight percents of Si, Al, Mg, Fe, FeO, Fe_2O_3, Fe_3O_4, Fe (metal), C, and H_2O are determined. Concentrations of elements and compounds are assumed to add linearly according to the percentage of each meteorite type in the combination except for the oxygen isotopic values. The ^{17}O (‰), ^{17}O (‰), and ^{18}O (‰) aggregate values are weighted by the oxygen concentration of each meteorite type.

For Earth and Mars, respectively, the values of the aggregate ^{17}O (‰), ^{17}O (‰), and ^{18}O (‰) are first checked against respective tolerances. Values falling within all of these tolerances are then checked against chemical constraints for each planet. For Earth, the bulk FeO (wt.%) and the bulk Fe/Al ratio were used. For Mars, just the bulk FeO (wt.%) was used. If the values are within the tolerances (called a "match"), the results are stored, and several counters are incremented.

To calculate the "true" bulk FeO of Earth and Mars, the effects of a number of redox reactions that should occur due to heating during planetary accretion need to be included in our analysis. Three redox reactions (equations 3-5) from Lodders and Fegley [1] and two reactions (equations 1 and 2) to account for Fe^{3+} were used. The ordering of the redox reactions is shown below:

$$(1)\ 6Fe_2O_3 + C \rightarrow 4Fe_3O_4 + CO_2$$
$$(2)\ 2Fe_3O_4 + C \rightarrow 6FeO + CO_2$$
$$(3)\ C + 2H_2O \rightarrow CO_2 + 2H_2$$
$$(4)\ Fe\ (metal) + H_2O \rightarrow FeO + H_2$$
$$(5)\ FeO + 0.5C \rightarrow Fe\ (metal) + 0.5CO_2.$$

A sixth reaction from Lodders and Fegley [1]

$$(6)\ SO_3 + 1.5C + Fe\ (metal) \rightarrow 1.5CO_2 + FeS$$

never occurs in our runs for Earth and Mars since carbon tends to be consumed in earlier reactions. Reaction 4 never occurs in our runs for Earth. As with Lodders and Fegley [1], it was assumed that all excess carbon and H_2O are converted to CO_2 and H_2, which escape. The calculated FeO was then renormalized to account for these lost gases. The redox reactions do not significantly change the concentrations of FeO for the matching combinations.

Data: We compiled average ^{17}O (‰), ^{17}O (‰), and ^{18}O (‰) for each meteorite type primarily from data of Clayton *et al*. [2] and Clayton and Mayeda [3]. Our chemical data was primarily compiled from the work of Jarosewich [4] who did wet chemical analyses of ~200 bulk meteorite samples. Jarosewich measured all major elements and reported the results primarily as oxides. Other phases are presented as sulfides, SO_3, CO_2, elemental sulfur, H_2O, Fe (metal), and Fe_2O_3.

Constraints: For the Earth, the oxygen isotopic constraints are ^{17}O (‰) = 0.00 $\pm$ 0.03, ^{17}O (‰) = 2.81 $\pm$ 0.26, and ^{18}O (‰) = 5.40 $\pm$ 0.50. The ^{18}O (‰) value is an estimate for the PUM (primitive upper mantle) [5]. For Mars, the oxygen isotopic constraints are ^{17}O (‰) = 0.32 $\pm$ 0.02, ^{17}O (‰) = 2.75 $\pm$ 0.26, and ^{18}O (‰) = 4.68 $\pm$ 0.50. The ^{17}O (‰) and ^{18}O (‰) values are the average values from the SNC meteorites from Franchi *et al* [6].

For Earth, the Fe/Al (wt. ratio) is assumed to be 20 $\pm$ 2 [7]. We also determine how far any chondritic mixture falls from the Earth's magmatic fractionation trend. Since chondritic meteorites have average Mg/Si and Al/Si ratios that are enriched in Si relative to this trend line, no mixture of chondritic material will fall on or near this line. No elemental ratio constraints are used for Mars.

The FeO constraint used for the Earth is 5.4 $\pm$ 0.5. This number is taken by assuming that the PUM has a FeO concentration of 8.0 wt.% [8] and assuming that the core is 32.5 wt.% of the mass of the Earth. The FeO constraint used for Mars is 14.4 $\pm$ 1.4. This number is taken by assuming the Martian mantle has a FeO concentration of 18.0 wt.% [8] and assuming that the core is 20% of the mass of Mars.

Results: For the constraints for Earth, there were 514 matches out of 225,792,840 possible combinations (0.00023%). The matches on average contain ~55% EL chondritic material. The high proportion of EL chondritic material in the matches is due to the Earth having similar oxygen isotopic properties and similar Fe/Al weight ratios to the EL chondrites and the Earth having a concentration of FeO intermediate between EL chondrites and most other chondritic meteorites. All other meteorite types have average abundances in the matching combinations of 10% or less.

However, as expected, none of our matches are good compositional analogs for the Earth if we use Mg/Si and Al/Si weight ratios. We plot the position of the matches in Mg/Si-Al/Si space (Fig. 1) and can see that the matches plot far away from the Earth's magmatic fractionation trend line. For the average Mg/Si and Al/Si values of the matches, ~32% of the Si needs to be removed to reach the Earth's magmatic fractionation trend line or the Mg and Al concentrations must be increased by a similar amount.

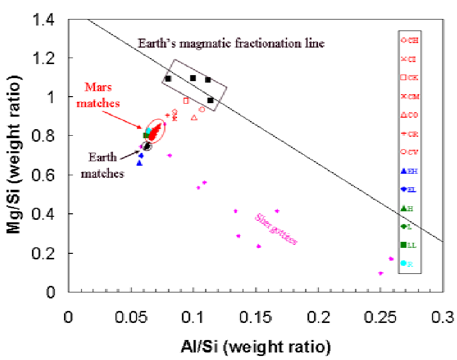

Fig. 1. Plot of Al/Si versus Mg/Si for average values of the chondritic meteorites, estimated values for the primitive upper mantle (black squares), and shergottite meteorites (pink diamonds). The black dots are the matches for the Earth and the red dots are matches for Mars.

The low number of matches is controlled by the low FeO concentration of the Earth compared to chondritic meteorites. There are 458,360 matches without the FeO constraint.

It is possible to match estimates of Earth's oxygen isotopic composition and its bulk Fe/Al weight ratio and FeO concentration using chondritic meteorites. However, as expected, the resulting bulk compositions calculated for the Earth plot far away from the Earth's magmatic fractionation trend line in Mg/Si-Al/Si space. Assuming the composition of the PUM falls on the Earth's fractionation trend line, it does not appear possible to make Earth out of known chondrites.

For the constraints for Mars, there were 165,357 matches out of 225,792,840 possible combinations (0.073%). The matches for Mars tend to be heavily weighted towards ordinary chondritic material. The H and LL chondrites, respectively, can make up to 80% and the L chondrites up to 75% of a particular matching combination due to these meteorites having roughly similar oxygen isotopic values and FeO concentrations as Mars.

We plot the position of the matches for Mars in Mg/Si-Al/Si space (Fig. 1) and, as expected, the matches for Mars plot near the points for ordinary and R chondrites. Interestingly, the trend for the Martian basaltic meteorites (shergottites) falls near where the matches for Mars plot. Our matches appear roughly consistent with the Martian magmatic fractionation trend line as defined by the shergottite meteorites.

Conclusions: Our rigorous modeling using hundreds of millions of possible combinations of chondritic material finds that it does not appear possible to match the Earth's assumed bulk chemical composition using known chondritic meteorites, but it is possible to match Mars' composition. Possible solutions [9] to this conundrum include forming the Earth out of material that is not currently found in our meteorite collections or sequestering some of the Earth's Si in the core and/or lower mantle.

References: [1] Lodders K. and Fegley B. Jr. (1997) *Icarus, 126,* 373-394. [2] Clayton R. N. et al. (1991) *Geochim. Cosmochim. Acta, 55,* 2317-2337. [3] Clayton R. N. and Mayeda T. K. (1999) *Geochim. Cosmochim. Acta, 63,* 2089-2104. [4] Jarosewich E. (1990) *Meteoritics, 25,* 323-337. [5] Eiler J. M. et al. (2000) *Nature, 403,* 530-534. [6] Franchi I. A. et al. (2000) *Meteoritics & Planetary Science, 34,* 657-661. [7] McDonough W. F. and Sun S.-s. (1995) *Chemical Geology, 120,* 223-253. [8] Robinson M. S. and Taylor G. J. (2001) *Meteoritics & Planetary Science, 36,* 841-847. [9] Drake M. J. and Righter K. (2002) *Nature, 416,* 39-44.