HETEROGENEOUS ACCRETION OF THE TERRESTRIAL PLANETS. D. C. Rubie[1], D. P. O'Brien[2], F. Nimmo[3], A. Morbidelli[4], D. J. Frost[1], and H. Palme[5], [1]Bayerisches Geoinstitut, University of Bayreuth, D-95440 Bayreuth, Germany, dave.rubie@uni-bayreuth.de, [2]Planetary Science Institute 1700 E. Ft. Lowell Rd., Tucson, AZ 85719-2395, [3]Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, [4]Observatoire de Nice, B.P. 4229, F-06304 Nice Cedex 4, France, [5]Forschungsinstitut und Naturmuseum Senckenberg, Senckenberganlage 25, D-60325 Frankfurt am Main, Germany

Introduction: According to current theories, planets accrete and accumulate mass through a series of impacts with smaller planetesimals and embryos [1]. Impacting embryos potentially provide sufficient energy to cause large scale melting, the establishment of a deep magma ocean and therefore an episode of metal-silicate segregation. Core formation in terrestrial planets must therefore have involved multiple metal-silicate equilibration events. The siderophile element budget of the Earth's mantle thus results from the cumulative effects of such a process. In contrast, models of single-stage core formation [2, 3], which imply a single metal-silicate equilibration event, are not consistent with accretion models and probably not with the composition of the Earth's primitive mantle [4, 5].
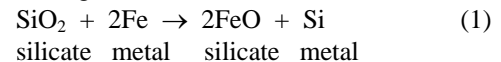
Multistage core formation: We have formulated a new multistage core-formation model, based on a simplified and idealized accretion scenario [5]. The Earth accretes through collisions with differentiated bodies that are approximated $0.1 \times$ Earth's mass at the time of the impact. After each collision, the impactor's core partially or completely equilibrates in a magma ocean before merging with the planet's proto-core. The impactors have bulk compositions with solar system (CI) element ratios for Si, Fe, Mg, Ni, Cr and Co and concentrations of the refractory elements Al, Ca, V, Nb, Ta and W that are enhanced relative to CI (based on the mantle Al/Mg ratio). The oxygen content of the bulk composition defines the initial metal/silicate ratio and is a fitting parameter in the model. As discussed below, bulk compositions are anhydrous.

Compositions of metal and silicate that result from the equilibration process are determined from the bulk composition by a novel approach involving a rigorous mass balance combined with element partitioning. The effective equilibration pressure P_e is defined to be some fraction of the core-mantle pressure at the time of the impact and thus increases during accretion. For the Earth, model parameters (e.g. metal-silicate equilibration P-T conditions and compositions of accreting material) are determined by a least squares fit based on constraints provided by the concentrations of the above 12 major and trace elements in the Earth's mantle [6].

In order to match the Earth's mantle concentrations of SiO_2, FeO, Cr and V, the initial 60-70% of Earth's mass formed from material that was highly reduced (>99% of Fe initially present as metal) and the final 30-40% from material that was more oxidized (~60% of Fe initially present as metal). Accretion was therefore *heterogeneous*. The reduced composition is considered to represent the average composition of material that originated in the inner regions of the solar nebula where temperatures were high, whereas the more oxidized material originates further out. The model is thus consistent with radial mixing in the solar system.

In addition to accreting material becoming more oxidized, the mantle FeO concentration of 8 wt% is achieved through the reaction [7]:

$$SiO_2 + 2Fe \rightarrow 2FeO + Si \qquad (1)$$
$$\text{silicate} \quad \text{metal} \qquad \text{silicate} \quad \text{metal}$$

This reaction shifts to the right as the Earth grows because Si dissolves increasingly into core-forming Fe metal as magma ocean depth and metal-silicate equilibration temperatures increase. The consequences are a progressive increase in the FeO content of the Earth's mantle (thus causing oxygen fugacity to increase by several orders of magnitude during accretion) and ~8 wt% Si in the Earth's core.

In order to match mantle concentrations of the siderophile elements Ni, Co and W, a high degree of *disequilibrium* is required in the case of large and late impactors: this means that the metallic cores of such impactors only partially re-equilibrated in the magma ocean before merging with the Earth's proto-core, as suggested previously [8, 9]

The present model is consistent with the moderately volatile elements being added during the accretion of the final 30-40% of Earth's mass [10, 11, 12]. The Earth's water inventory was also accreted at a late stage. Early accretion of H_2O can be excluded because this would have resulted in an increase in oxidation state that is inconsistent with the present model.

Terrestrial planet core formation: The core-mantle differentiation model is currently being combined with the results of N-body accretion simulations [13] in order to compare the chemical evolution of terrestrial planets that form at different heliocentric distances in the solar system. These simulations commenced with 25 Mars-size embryos and ~1000 smaller planetesimals that were distributed initially between 0.3 and 4 AU. Two sets of simulations were performed, one in which the orbits of Jupiter and Saturn

were circular (CJS) and the other with these orbits being eccentric (EJS). From each set, we have selected a simulation that produces a planet of ~1 Earth mass at ~1 AU (CJS2, planet #6; EJS3, planet #5).
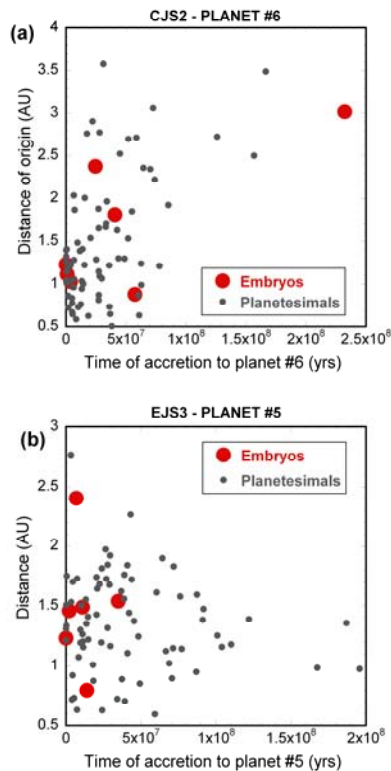

Fig. 1. The timing of the accretion of planetesimals and embryos to the most Earth-like planet in simulations CJS2 (a) and EJS3 (b) of [13] as a function of the location of origin of these bodies in the early solar system.

Fig. 1 shows the timing of accretion of planetesimals and embryos to the two Earth-like planets as a function of their original location in the solar system. The CJS results (Fig. 1a) show a general trend whereby bodies that accrete late originated relatively far from the Sun. The EJS result (Fig. 1b) shows no such trend, largely due to the rapid clearing of the asteroid belt region. The core-formation model described above is most consistent with the CJS result.

We assume that bodies originating in the inner solar system (e.g. at <1.5 AU) have a reduced composition whereas bodies that form at greater distances are more oxidized. The oxidation state and its dependence on location are fitting parameters in the model. Preliminary results obtained from combining the core-formation model with results of the CJS2 simulation show a strong correlation between mantle chemistry, core size and the final heliocentric distance of a planet. The FeO content of the planetary mantles increases

from 4 to 14 wt% and the Mg/Si ratio decreases from 1.14 to 0.96 as heliocentric distance increases from 0.5 to 1.9 AU (Fig. 2). Correspondingly, the mass of the planetary cores decreases from 34% to 24%. These trends are broadly consistent with values for Earth, Mars and, to some extent, Mercury. The cause of the trends is that more oxidized material is accreted to planets that form at greater heliocentric distances. This results in a higher oxygen fugacity, more FeO in the mantle, less Si in the core and a lower Mg/Si ratio.
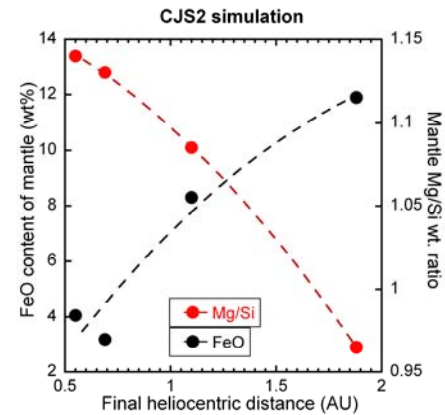

Fig. 2. Mantle FeO concentrations and Mg/Si wt. ratios for four planets from N-body accretion simulation CJS2 of [13]. The planet at 1.1 AU has a location, mass and mantle composition comparable to that of the Earth. In contrast, clear systematic trends were not obtained for the EJS3 planets.

An additional factor that can effect the trends of Fig. 2 is planet size because this determines *P-T* conditions of metal-silicate equilibration and the extent of reaction (1). The planet at 1.9 AU in Fig. 2 has a mass ~6 × the mass of Mars. If this planet were considerably smaller (i.e. Mars size), there would be less Si in the core, the mantle FeO concentration would be higher and the core would be smaller.

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