ACCRETION AND DIFFERENTIATION OF THE TERRESTRIAL PLANETS: IMPLICATIONS FOR THE COMPOSITIONS OF EARLY-FORMED SOLAR SYSTEM BODIES.

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Introduction: The accretion of the terrestrial planets of our Solar System occurred on a timescale of 10-100 My through numerous high-energy collisions with Moon- to Mars-size planetesimals and embryos. This process is modelled numerically using N-body simulations in which up to 80 planetary embryos and several thousand planetesimals, initially distributed in a disk that extends outwards from the Sun, collide to form the terrestrial planets [1,2]. In contrast to earlier studies, the "Grand Tack" model, based on the early inward and then outward migration of Jupiter and Saturn, is particularly successful [3]. The Grand Tack simulations produce, in 30-100 Ma, terrestrial planets on orbits consistent with the real ones and, in particular, they explain why Mars is ~10 times smaller than the Earth and formed ~10 times faster.

In order to provide new tests of the validity of such simulations, we are the combining N-body accretion results with models of planetary core-mantle differentiation. This enables model mantle compositions to be determined for the terrestrial planets in a given accretion simulation that can then be compared with the actual compositions. The high energy of impacts during planetary accretion was sufficient to cause large-scale melting and deep magma ocean formation which facilitated the segregation of molten metal and silicate. Planetary cores thus formed as a multistage process that was inseparable from the accretion process. In order to model the formation and early differentiation of the terrestrial planets, we are integrating a multistage core-formation scenario [4] with accretion simulations [3]. A primary aim is to determine if a model Earth-like planet, at ~1 AU, can be accreted with a mantle composition that is identical or similar to that of the Earth's mantle.

Methods: We use an element partitioning/mass balance approach in which it is necessary to assign a bulk composition to each of the starting embryos and planetesimals [4]. We assume that all bodies are similar in having solar-system (CI) relative abundances of non-volatile elements and that the oxygen content is the main compositional variable. Compositions can be varied from highly-reduced, with all Fe is present as metal, to fully-oxidised with all Fe present as FeO in silicate. A basic assumption is that the oxygen content of primitive bodies varies systematically as a function of their heliocentric distance of origin – i.e. the compositional variation is not random.

Each collision between an embryo and another body in the accretion simulations is considered to result in magma ocean formation and an episode of core formation. Based on the bulk compositions of the two bodies, we determine the compositions of equilibrated metal and silicate liquids at the equilibration pressure P_e (which is a fitting parameter in the model that is determined by a least squares minimization). The compositions of the two liquids are expressed as:

$$\underbrace{[(FeO)_x\,(NiO)_y\,(SiO_2)_z\,(Mg_u\,Al_m\,Ca_n)O]}_{\text{silicate liquid}} + \underbrace{[Fe_a\,Ni_b\,Si_c\,O_d\,]}_{\text{metal liquid}}.$$

Here the indices u, m and n are determined from the bulk composition because Mg, Al and Ca are lithophile elements and do not partition into metal. The other seven indices, x, y, z, a, b, c and d, are determined using four mass balance equations (for Fe, Si, Ni and O), two expressions for the metal-silicate partitioning of Si and Ni [4] and a thermodynamic model for oxygen partitioning at high pressure [5]. For each core-formation episode, the equilibrated metal is added to the embyro's proto-core and the equilibrated silicate is added to the mantle.

Contrary to previous models of core formation, we do not assume that the metallic cores of impactors equilibrate with the entire silicate mantle of the target body. Even for a giant Moon-forming impact, a significant part of the target planet can be unaffected by the collision [6,7]. In addition, an impactor's core is expected to sink through a magma ocean as an expanding plume that turbulently entrains silicate liquid so that the amount of silicate that equilibrates increases with depth [8]. We thus use the model of [8] to determine the fraction of an embroyo's mantle that equilibrates with the impactor's core. Typically, this fraction is small and ranges from 0.001-0.02 for planetesimal impacts to 0.04-0.07 for embryo impacts. For the results presented here, we assume that all the metal of impactors' cores emulsifies and equilibrates fully with this restricted amount of silicate liquid.

Constraints on model parameters are the compositions of the Earth's primitive mantle and, to a lesser extent, the mantles of Mars and Mercury which are considered to be FeO-rich and FeO-poor respectively. In order to match the constraints, we use a least-squares minimization to optimise up to 4 model parameters. These consist of the metal-silicate equilibration pressure P_e and 1-3 parameters that describe the oxygen content of the original embryos and planetesimals as a function of their heliocentric distances of origin. Elements currently used for fitting are Fe, Si, O, Ni, Co, Nb, Cr, Ta and V. We concentrate here on the Grand Tack simulation SA154_767 in which starting planetesimals were distributed between 0.7 and 13 AU. This simulation produced four final planets including an approximately Earth-mass planet at 1 AU and an outer Mars-mass planet at 1.68 AU.

Results: In order to investigate the broadest possible parameter space, we consider three possible composition-distance models for the starting bodies. (1) Oxygen content is constant as a function of heliocentric distance, which is the requirement for homogeneous accretion. (2) Bodies that originate close to the Sun are oxidised and those originating further out are relatively reduced. (3) Bodies that originate close to the Sun are reduced and those originating further out are relatively-oxidised. In the case of models (1) and (2), it is not possible to create an Earth-like planet with a mantle composition close to that of the Earth's mantle and reduced chi squared values in the range 70-80 are obtained for the best fits. Model (3), on the other hand, results in excellent fits for all elements, giving reduced chi squared values in the range 1.5 – 3.0 with metal-silicate equilibration pressures ~60% of core-mantle boundary pressures. In addition, in marked contrast to models (1) and (2) a realistic Martian mantle FeO content of 18-20 wt% is obtained. However, it is not possible to define a unique composition-distance model in category (3). Two variations, which give equally good results, are shown in Fig. 1. In both cases, all Fe is initially present as metal in reduced compositions. In addition, up to 20% of available Si is initially dissolved in the metal – which further reduces the oxygen content. Fig. 1a shows a "step" model in which compositions beyond 1.7 AU are partially oxidized whereas Fig. 1b shows a "gradient" model in which compositions become increasingly oxidized between 1.2 and 3.1 AU and are fully oxidized beyond 3.1 AU.

Composition-distance models, such as those shown in Fig. 1, can be justified as follows. Oxygen fugacities of a solar gas are orders of magnitude more reducing than the intrinsic oxygen fugacities at which the terrestrial planets and meteorite parent bodies formed but are consistent with the region of highly-reduced compositions at <1-1.5 AU shown in Fig. 1. Thus extensive oxidation must have occurred in the early solar system with oxidation of Fe to form an FeO component in silicates being the major consequence. The most likely oxidant was water. The oxidation gradient shown in Fig. 1b can be explained as follows: Due to the net inflow of material in the solar nebula, ice-covered dust moves inwards from beyond the snow line. Inside the snow line, water ice sublimes, thus adding H_2O to the vapour phase. As temperatures continue to rise and material continues to move inwards, H_2O-rich vapour reacts with Fe-bearing dust which results in oxidation. Inward still, vapour is H_2O-poor because the products of sublimed water ice have not mixed all the way to the innermost solar system. Here Fe remains free of oxidation and highly-reduced compositions are preserved.

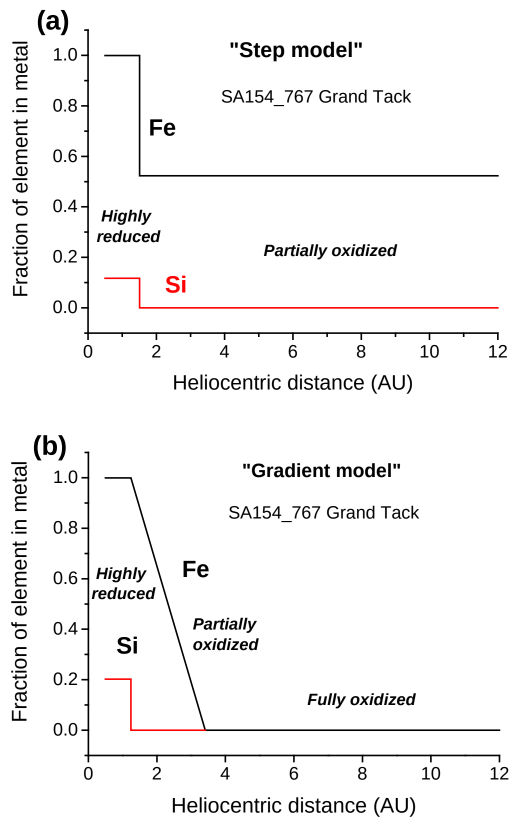

Figure 1. Two alternative composition-distance models that give equally good fits to the Earth's mantle composition in a combined N-body accretion simulation/multistage core formation model. In both cases, bodies in an inner region have highly reduced compositions with all Fe being present as metal and a significant proportion of available Si being dissolved in metal. Beyond 1-1.5 AU, compositions are more oxidised.

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