THE TROUBLE WITH BUILDING PLANETS TOO QUICKLY: RAPID ACCRETION IN GRAND TACK SIMULATIONS REQUIRES EXTREMELY EFFICIENT MANTLE EQUILIBRATION OF HF-W.

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Summary: We follow the evolution of the Hf/W isotopic system through 141 N-body accretion simulations using the Grand Tack scenario, during which we vary the degree that impactor cores are assumed to re-equilibrate with the mantles of target bodies. The results reproduce the measured tungsten isotope values for resulting Earth and Mars-sized bodies only if impactor cores are assumed to equilibrate nearly completely with target mantles. This stipulation is necessary because the bulk of accretion finishes earlier than in classical simulations.

Introduction: Measurements of the extinct Hf/W isotopic system in meteorites and the Earth can be used to place constraints on the timescales of core formation and accretion [1]. Simulations of the tungsten isotopic evolution for planetesimals in "classical" accretion models have produced values close to those measured presently on the Earth assuming intermediate equilibration between core and mantle [1,2]. These classical models have trouble consistently reproducing the mass of Mars, which inspired the creation of the Grand Tack scenario wherein Jupiter's migration truncates the disk and causes greater mixing in the inner solar system [3,4]. In this study we examine the equilibration requirements needed for Grand Tack simulations to reproduce measured tungsten anomalies in final planets resembling Earth and Mars.

Mantle Equilibration: Hf is a lithophile and W a siderophile element, resulting in fractionation during core formation. We define the mantle fractionation factor with respect to stable Hf/W isotopes, normalized to a chondritic undifferentiated reservoir, CHUR:

$$f^{Hf/W} = \frac{\left({}^{180}Hf/{}^{183}W\right)_{mantle}}{\left({}^{180}Hf/{}^{183}W\right)_{CHUR}} - 1$$

The decay of ^{182}Hf into ^{182}W with a half-life of 9 Myr causes mantles with early core formation to develop a large positive tungsten anomaly [5]. The tungsten evolution of the mantle depends on how impactor core material re-equilibrates during each individual impact with a target [1,2]. The equilibration factor k is defined as the fraction of impactor core not directly added to target core, where $k = 0$ indicates core merging, and $k = 1$ indicates complete re-equilibration. If only a fraction of the target mantle equilibrates with the impactor core, the effective k is reduced.

Isotopic Results:

Initial mass distribution	*Mantle fractionation*	*Tungsten anomaly*	*Accretion time (Myr)*	*N*
Earth	**13.6 ± 4.3**	**1.9 ± 0.1**	-	-
1:1	14.1 ± 0.3	1.6 ± 0.5	27.7 ± 10.4	56
2:1	13.9 ± 1.3	2.1 ± 0.8	29.9 ± 29.3	53
4:1	13.9 ± 1.4	2.5 ± 1.0	30.4 ± 31.5	55
8:1	13.9 ± 1.2	2.9 ± 1.7	34.5 ± 36.7	81

Table 1: Summary of results for simulations with complete metal equilibration (k = 1.0). Mean and standard deviation for final values of bodies are displayed for objects that meet Earth-like criteria (mass within a factor of 2 of actual, semi-major axis between 0.387 and 1.524 AU). Measured Earth values from [6], [7], [8]. Initial mass is the ratio of mass in embryos vs. smaller planetesimals, and accretion time refers to the average time when a body reached 90% of final mass.

Fig. 1 shows the mantle fractionation factor as a function of semi-major axis, with the solid line representing the initial assumed values (from [5]). This initial variation in $f^{Hf/W}$ is one way of explaining the different values measured for Earth and Mars [6], [7], [8].

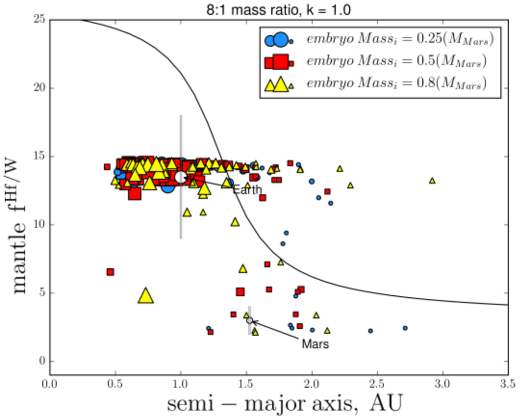

Figure 1: Mantle fractionation factor of surviving bodies as a function of final semi-major axis, for simulations where initial mass distribution is 8:1 embryo mass

to smaller planetesimal mass [3]. The solid line denotes initial assumed variation in $f^{\,\mathrm{Hf/W}}$ [5]. Embryo mass (shape type/color) refers to the initial size of embryos. The size of the markers is scaled to the object's final mass. Earth and Mars values appear as white circles with error bars.

In Fig. 2, the variation in mantle fractionation $f^{\,\mathrm{Hf/W}}$ against tungsten anomaly ε^{W182} is shown for k = 1. Tungsten anomaly increases with increased $f^{\,\mathrm{Hf/W}}$ (more Hf producing W in mantle) but decreases with longer accretion timescales, as expected. Although most model Earth-mass bodies develop large ε^{182W} values because of their rapid accretion, some take longer to complete accretion and are able to produce Earth-like values. Mars analogues accrete rapidly but can develop Mars-like ε^{182W} values because of lower $f^{\,\mathrm{Hf/W}}$ values. Smaller values of k (less equilibration) result in average isotopic anomalies which are too large.

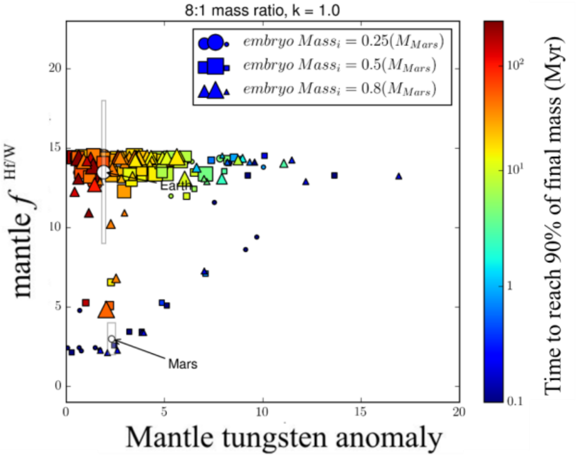

Figure 2: Mantle fractionation factor of surviving bodies as a function of tungsten anomaly, for scenarios using complete mantle equilibration (k = 1). Color scale shows approximate time of last giant impact, while size scales with final mass. Earth and Mars values (shergottite source) are plotted as white circles with error bars.

A summary of the effects of varying k is shown by plotting the mean tungsten anomaly ε^{W182} vs. equilibration factor k. Lower equilibration factors result in larger tungsten anomalies. High efficiency in re-equilibration (k ~ 1.0) is the only scenario that can reproduce current measurements of Earth and Mars.

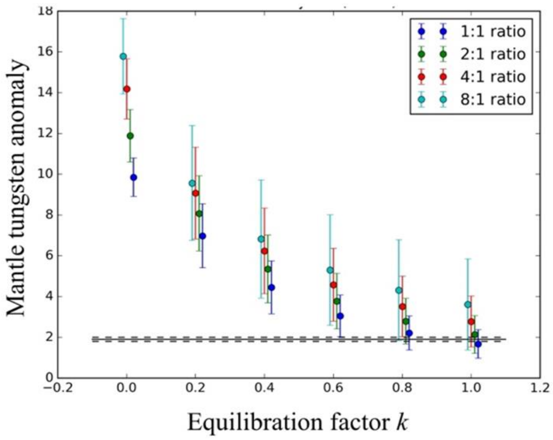

Figure 3: Average tungsten anomaly of surviving bodies as a function of the equilibration factor k. The value and uncertainty of tungsten anomaly for Earth is shown in solid and dashed lines, respectively.

Discussion: This study suggests that the Grand Tack scenario has difficulty constructing an Earth and Mars that have both physical and chemical characteristics that reasonably agree with measured values, unless we can assume mantle re-equilibration is very efficient and occurs with a factor of around k = 1.0. Fluid dynamics experiments [9] suggest that the effective k should be less than 1, and decrease with impactor size. There is thus a contradiction between the Grand Tack results and expectations of re-equilibration based on fluid dynamics. More experimental investigations of re-equilibration during impacts are clearly desirable. Future theoretical work should test more sophisticated treatments of how partitioning and $f^{\,\mathrm{Hf/W}}$ are likely to vary (for instance, as a function of the oxidation state and pressure and temperature of the evolving bodies [10]).

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