HF/W ISOTOPIC EVOLUTION FROM N-BODY ACCRETION SIMULATIONS: CONSTRAINTS ON EQUILIBRATION PROCESSES DURING LARGE IMPACTS. F. Nimmo, *Dept. Earth Sciences, University of California Santa Cruz, CA 95064, USA, (fnimmo@es.ucsc.edu)*, C.B. Agnor, *Dept. Earth Sciences, University of California Santa Cruz, CA 95064, USA, (cagnor@es.ucsc.edu)*, S. Raymond, *LASP, University of Colorado, Boulder,CO 80309-0392, USA (raymond@lasp.colorado.edu)*.

Introduction The hafnium-tungsten (Hf-W) isotopic system provides a powerful constraint on accretion and core formation timescales [1-3]. However, most estimates of these timescales employ analytical expressions assuming either continuous planetary growth or instantaneous core formation. In contrast, dynamical modelling of planetary accretion suggests that the final stage of terrestrial planet formation is punctuated by multiple large and stochastic impacts [4-6]. Such giant impacts have significant thermal and isotopic consequences. We have developed a framework [7], similar to that of [3], for calculating the Hf-W isotope evolution of individual bodies based on the results of N-body accretion simulations. We find the closest agreement between model results and observations if even the largest impactors undergo re-equilibration with the mantle of the target body.

Methods Two physical processes are responsible for the isotopic anomalies generated during core formation [7,8]. The first is fractionation; the second is radioactive decay. If fractionation occurs while the radioactive parent element (e.g. ^{182}Hf) is still extant ($t_{1/2}$=9 Myr for the Hf-W system), isotopic anomalies result due to the subsequent ingrowth of the daughter element (e.g. ^{182}W) in the mantle (which has high Hf/W). Such anomalies may be detected at the present day.

Regarding fractionation, some elements partition into silicates during differentiation (e.g. Hf), others prefer metals (e.g. W). For the case of an initially homogeneous object which differentiates into core and mantle, mass balance considerations and the definition of the partition coefficient D^i give

$$C'^i_m = \frac{C^i}{y + \frac{(1-y)}{D^i}} \quad , \quad C'^i_c = \frac{C^i}{1 + y(D^i - 1)} \qquad (1)$$

Here C^i and C'^i are the concentrations of the element i before and after differentiation, respectively, y is the silicate mass fraction (y may vary from body to body), and the subscripts m and c refer to core and mantle as before. We generally assume a constant value for each D^i, though this may be relaxed if desired. Irrespective of whether a collision occurs, the isotopic concentrations will also change over time due to the progressive decay of ^{182}Hf to ^{182}W.

During a collision, mass-balance considerations may be used to update the isotopic concentrations in the core and mantle of the resulting object [7]. Crucially, these concentrations will vary depending on the extent to which the impactor re-equilibrates with the mantle of the target prior to core separation and merging occurring [1-3].

Results Fig. 1a shows growth curves for planetesimals in an N-body accretion simulation [4]. Four planets (A-D) result, each of which suffers several giant impacts during the final stages of accretion (the two largest impacts are marked with arrows). Fig. 1b shows the resulting evolution of the tungsten isotopic anomaly, assuming that each impact results in core formation for previously undifferentiated objects, followed by instantaneous merging of the cores and mantles of the two bodies. Fig. 1c shows the results assuming that the impactor re-equilibrates with the mantle of the target, prior to core merging occurring. Fig. 1d summarizes the results of the two sets of calculations, and demonstrates that the "primitive differentiation" scenario (Fig. 1b) generally results in higher tungsten anomalies than the "mantle re-equilibration" scenario (Fig. 1c). Which of these scenarios is more likely depends on the details of the impact process, in particular the mixing length-scale, which are currently very poorly understood [8-9]. The size of the resulting isotopic anomalies will also depend on the partitioning coefficients D^i (which depend on oxidation state), and the silicate mass fraction.

Fig. 2 shows a set of results in which 1) even the largest impactors undergo re-equilibration with the target's mantle, rather than the cores merging directly, and 2) the original planetary embryos possessed radially variable iron:silicate ratios (but constant partition coefficients). The results are consistent with the observed physical and isotopic characteristics of inner solar system bodies (e.g. compare particle G to Earth).

Fig. 2a plots the model mass vs. tungsten anomaly for a set of five different accretion simulations [4], and compares it with the available observations (black squares). In general, the agreement between observations and model results is satisfactory. The isotopic variability of smaller bodies is larger than that for larger bodies. Fig. 2b plots the tungsten anomaly against the Hf/W ratio and demonstrates that, as expected, higher Hf/W ratios tend to result in larger tungsten anomalies. The variable Hf/W ratio results from the spatial variability in silicate mass fraction, shown in Fig. 2c. The initially imposed variability (dotted line) has been smeared out but not completely destroyed during the accretion process. The low silicate mass fraction of Mercury is not reproduced, because the model does not include the fragmentation processes likely responsible for Mercury's anomalously large core [10].

Discussion The agreement between the model results and the available observations (Fig. 2) suggests that simple core merging does not happen even in the very largest impacts. If it did, tungsten isotope anomalies larger than those observed would result (Fig. 1d). Thus, taken at face value our results may be used to constrain the poorly-understood processes which occur during large impacts. However, it is possible that varying either W partition coefficients (due to changing mantle oxidation state) [2] or initial planetesimal Hf/W ratios might produce similar isotopic outcomes, and potentially permit core mergers without violating the isotopic constraints.

For large bodies, similar results to Fig. 2 are obtained even if early differentiation of planetesimals occurs (e.g. due to decay of ^{26}Al [11]), as long as subsequent mantle re-equilibration takes place. However, if core merging occurs, the resulting iso-

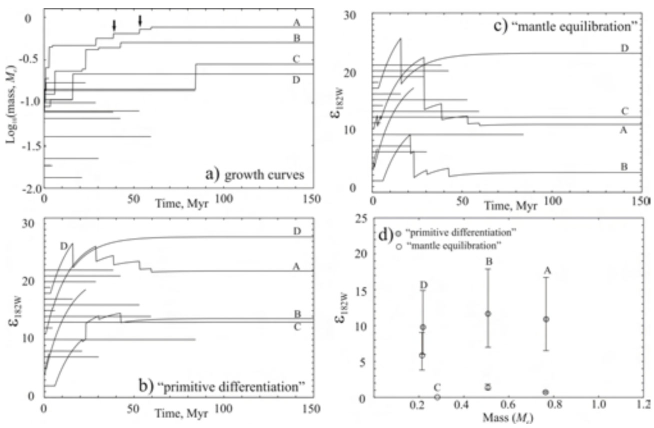

Figure 1: a) Growth curves of particles in N-body simulation (run 5 from [4]), plotting log10 mass (M) in units of one Earth mass (M_e) against time. Curves are truncated when particle merges with larger particle. A-D refer to bodies surviving at the end of the simulation. Individual curves have different line styles according to which final body each particle accretes to. Arrows denote two largest impacts. b) Evolution of ϵ_{182W} for individual particles, assuming primitive differentiation. Values for successive particles are offset by one ϵ-unit for clarity. Here the silicate mass fraction y=0.68 and $f^{Hf/W}$=12 for all particles. Initial concentrations relative to ^{183}W for ^{182}Hf, ^{182}W and ^{180}Hf were 2.836×10^{-4},1.850664, 2.836, respectively, and partition coefficients were $D^{Hf} = 10^4$ and $D^W = 0.0392$. c) As for b), but assuming "mantle equilibration". d) Summary of results from b) and c), plotting final particle mass M against ϵ_{182W} for two different re-equilibration scenarios. Range of values obtained by varying y from 0.78 (low ϵ_{182W}) to 0.58 (high ϵ_{182W}).

topic anomalies are too large [7]. Similarly, preliminary results with higher-resolution N-body simulations suggest that Martian isotopic anomalies are also more easily reconciled with mantle re-equilibration than with core merging.

The style of equilibration is likely to depend both on the size and state of the target, and the relative sizes of the colliding bodies. For large bodies, mantle re-equilibration likely indicates the presence of magma oceans [8]. For smaller bodies, an alternative is that the bulk of the mass was delivered as impactors much smaller than the target, consistent with the runaway growth phase of accretion [12].

The results presented here are preliminary in several respects. Future work should concentrate on 1) using larger numbers of smaller initial planetesimals [6,13]; 2) incorporating other isotope systems to use as additional constraints (e.g. Pd-Ag or U-Pb); 3) investigating the effects of variability in partitioning, and variability in equilibration as a function of body mass; 4) coupling the isotopic calculations to thermal evolution calculations.

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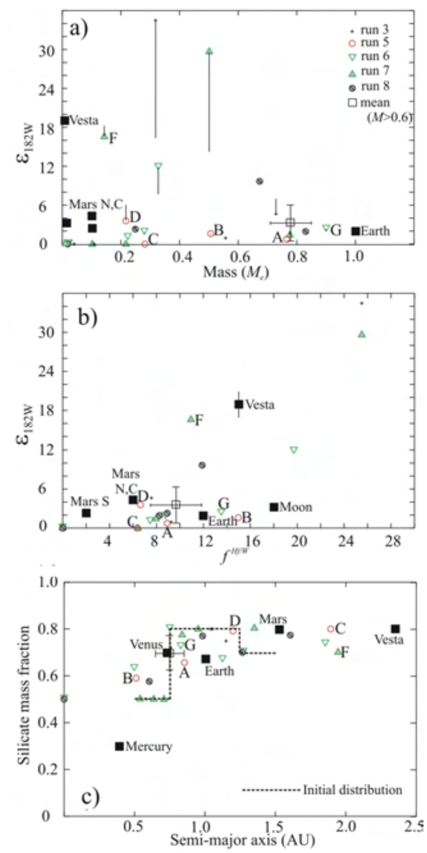

Figure 2: Isotopic outcomes from 5 accretion runs (coloured symbols) compared with observations (black squares). Model results assume constant partition coefficients, spatially variable silicate mass fraction y and mantle re-equilibration for all collisions. a) Final mass vs. tungsten anomaly. The open box and error bars denote model mean and standard deviation for bodies with $M \geq 0.6M_e$. Particles A-D are shown in Fig. 1. Vertical lines plot differences to case when y is constant. b) Tungsten anomaly versus mantle Hf/W ratio. c) Silicate mass fraction versus semi-major axis. Dotted line denotes initially imposed variation.