EROSION DURING ACCRETION: CONSEQUENCES FOR PLANETARY IRON-SILICATE RATIOS AND TUNGSTEN ISOTOPE ANOMALIES. C.A. Dwyer, F. Nimmo, E. Asphaug, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz, CA 95064 (cadwyer@ucsc.edu)*, D.P. O'Brien, *Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85179* .

Introduction The late stages of planetary accretion involve stochastic, large collisions [1]. Although such collisions are usually assumed to result in perfect mergers, many of the collisions may instead result in hit-and-run events [2] or erosion of existing bodies' mantles [3]. Impact-related erosion and fragmentation can have profound consequences for the rate and style of accretion [4] and the bulk chemistries of terrestrial planets [5]. Here we present some preliminary investigations into the occurrence of erosional collisions during late-stage accretion and consequences for the bulk chemistry and isotopic characteristics of the resulting planets.

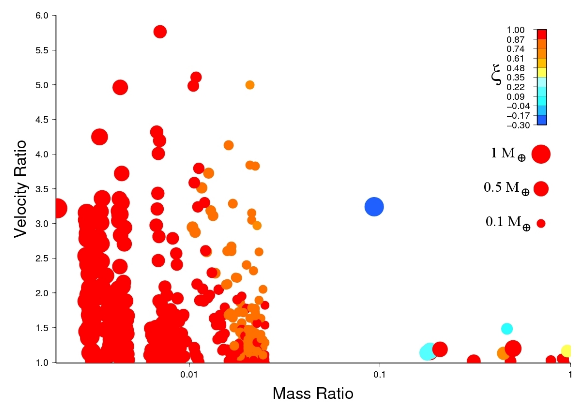

Figure 1: Accretion efficiency ξ as a function of impactor:target mass ratio and velocity ratio for the CJS1 model of [6]. Dot size is scaled by the cube root of the target mass. The vast majority of impacts are highly accretionary ($\xi \approx 1$).

Method To investigate the nature of late-stage collisions, we used the N-body simulation results of O'Brien et al. [6], which begin with mass evenly distributed between roughly Mars-mass embryos and Moon-size planetesimals. This code assumes perfect mergers, so our approach is not fully self-consistent; nonetheless, it provides an initial insight into the likelihood of erosional collisions.

Erosion/accretion is parameterized based on the results of [7]. Accretion efficiency is defined as $\xi = (M_f - M_t)/M_i$, where M_f, M_t and M_i are the masses of the final body, target body and impactor respectively. Thus, $\xi = 1$ implies complete merging, while $\xi = 0$ defines the boundary between accretion and erosion. In this work, we have assumed that eroded material is removed from reservoirs in the following order: impactor mantle, target mantle, impactor core and target core. Although *ad hoc*, this assumption is in agreement with SPH simulations [3,8] in which core erosion is very difficult to achieve, due mainly to the large density contrast between iron and silicate. We assume that material which is eroded is immediately lost from the entire system, with no possibility of being reaccreted onto any body in the future.

It was shown in [7] that ξ depends on V_r, the ratio of the impact velocity to the two-body escape velocity; θ, the angle of impact, where zero degrees is a head-on collision; and γ, the impactor:target mass ratio. In this work, when $V_r \in [1, 3]$ and/or $\theta \in [0°, 60°]$ and/or $\gamma \in [0.1, 1]$, ξ was determined from the results of [7] using linear interpolation. If a parameter(s) lay outside this range, the value at the bound was used for that parameter, with the exception of γ. We assumed that for impactors sufficiently smaller than the target, accretion would be total. Thus, $\xi = 1$ for γ below some critical mass fraction γ_c. A linear interpolation was applied for $\gamma \in [\gamma_c, 0.1]$. A value of 10^{-5} was used for γ_c here.

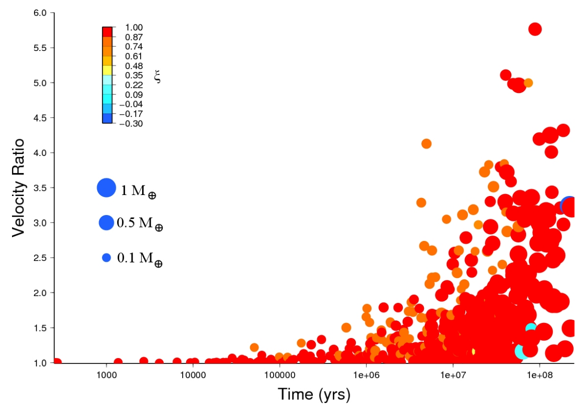

Figure 2: As for Figure 1 but plotting accretion efficiency as a function of time and velocity ratio.

All bodies are assumed to have started with identical iron:silicate mass ratios (y = silicate/(silicate+iron)) and to have differentiated at time zero. The subsequent evolution of y for individual bodies was calculated by evaluating the effect of each collision using the parameterization of ξ outlined above. In order to investigate the tungsten isotopic evolution of these bodies during impacts, we assumed complete equilibration of the impactor with the mantle of the target. Equation (12) of [9] was employed to determine the isotopic effect of each collision and equation (74) of [10] was used for the isotopic evolution between collisions. The tungsten partition coefficient D_W was assumed to be constant at 30, but the Hf/W fractionation factor $f^{Hf/W}$ was calculated depending on y of the post-impact body according to $f^{Hf/W} = (D_W)(1 - y)/y$.

Results With the above parametrization of the fragmentation process, all impacts save one are found to be accretionary ($\xi > 0$), with many being highly accretionary. In Figures 1 and 2, the color of the dots is scaled by the accretion factor and the size goes as the cube root of the mass. Figure 1 shows the mass dependency of the collisions. The vast majority of impacts occur at low mass ratio, indicating collisions between planetesimals and embryos, over a range of V_r values. These impacts tend to be highly accretionary. There are a few impacts at higher mass ratios, which are between two embryos and occur predominantly at low V_r. Even with similar impact velocities, embryo-embryo impacts range from erosional to highly accretionary, due in large part to the variability in θ of these collisions.

Figure 2 shows V_r plotted against time on a semi-log plot. As time proceeds, the velocity ratio of collisions increases, because of the reduction in dynamical friction as the number of surviving planetesimals decreases. However, this increase in V_r is offset by a corresponding decrease in γ (since the embryos are growing in size but the planetesimals are not). As a result, the majority of these late-stage collisions are still highly accretionary.

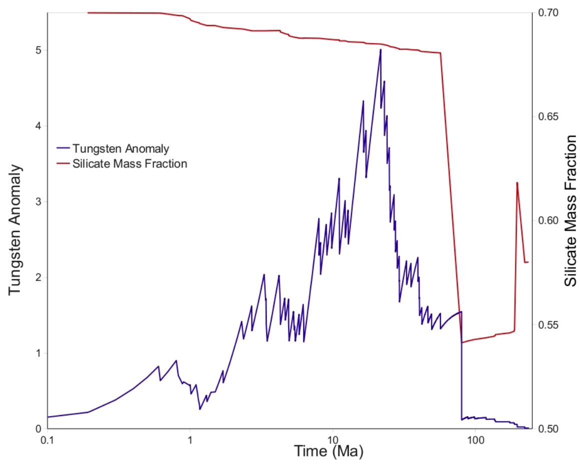

Figure 3: Time evolution of tungsten anomaly ε_W and silicate mass fraction y for a single body (the innermost body of CJS1 of [6]) undergoing incomplete accretion. Note that the time axis is logarithmic. The initial silicate mass ratio (y) was set to 0.7.

The time-evolution of the tungsten anomaly with respect to chondritic (ε_W) of the mantle of an example body is plotted on Figure 3. Because we are assuming complete re-equilibration of the target, each collision results in a reduction in ε_W with larger reductions arising from collisions with larger objects. Partial equilibration would result in a smaller change per impact, which would in turn result in a larger final ε_W. Note that in general, if the initial y is larger, ε_W will be smaller and so will the reduction in ε_W during an individual collision.

For the body plotted in Figure 3, there were three embryo-embryo impacts and 66 planetesimal-embryo impacts. The three embryo-embryo impacts occur comparatively late (>80 Ma) and show a range of behavior. The first one occurs at 80 Ma and is only just barely accretionary (ξ = 0.014), which is why there is such a sharp drop in y at this time. The silicate mantle is enriched by the planetesimal impacts which occur following that, as those impacts were accretionary ($\xi \geq 0.90$) and planetesimals have primordial y values (by construction). The next embryo-embryo impact occurred with a body which had a much higher y value and was strongly accretionary (ξ = 0.96), which resulted in an increase in y for the body. The very next impact was also embryo-embryo and was the sole erosional impact of this simulation (ξ = -0.26), perhaps similar to a hypothesized mantle-stripping impact on Mercury [3]. Because complete re-equilibration is assumed, all planetesimal-embryo impacts contribute to the reduction in ε_W of the final body.

In Figure 4, the model ε_W of the bodies still existing at 0.25 Ga has been plotted against their final y using both incomplete accretion (initial y = 0.8, 0.7) and total accretion (y = 0.8, 0.7, 0.6), as well as the values known for terrestrial bodies. Our model ε_W values are all smaller than those measured; however, relaxing the assumption of complete re-equilibration will increase the magnitude of the final computed ε_W.

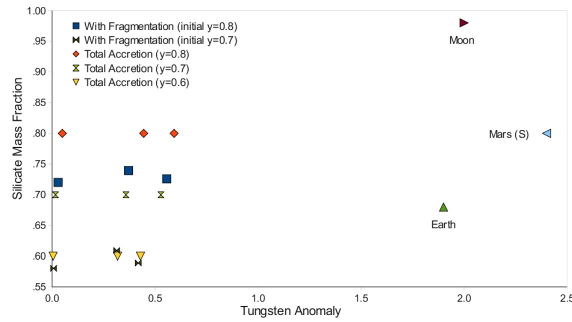

Figure 4: Silicate mass fractions against ε_W for the three final bodies from CJS1 and selected solar system objects. Model values for both complete accretion ($y = 0.6, 0.7, 0.8$) and incomplete accretion (initial $y = 0.7, 0.8$) are shown.

Mantle erosion perturbs the resulting ε_W values compared to the constant-y cases. This effect is relatively small, but is likely to be much more important for elements concentrated in the crust, which are more susceptible to erosion [5].

For the models with fragmentation, the scatter among final y values is much smaller than that observed in the solar system. Examination of the time-history of y for all three surviving bodies suggests that this is is a coincidence due to the precise impact characteristics. As such large impacts are stochastic in nature, we anticipate that other simulations will reveal a higher scatter in y.

Future Work To proceed further, a self-consistent accretion model including fragmentation is required (e.g. [4]). Relaxing the assumption of complete re-equilibration requires the isotopic evolution of all bodies to be tracked simultaneously. Tracking crustal growth and erosion would greatly expand the number of elements that can be used as observational constraints [5].

References

[1] Agnor, C.B. et al., Icarus 142, 219-237, 1999.
[2] Asphaug, E. et al., Nature 439 155-160, 2006.
[3] Benz, W. et al., Space Sci Rev 132, 189-202, 2007.
[4] Chambers, J., Icarus 198, 256-273, 2008.
[5] O'Neill, H.St.C. and H. Palme, Phil Trans R Soc A 366, 4205-4238, 2008.
[6] O'Brien, D.P. et al., Icarus 184, 39-58, 2006.
[7] Asphaug, E., Annu Rev Earth Planet Sci 37, 413-448, 2009.
[8] Canup, R.M., Phil Trans R Soc A 366, 4061-4075, 2008.
[9] Kleine, T. et al., GCA 73, 5150-5188, 2009.
[10] Jacobsen, S.B, Annu Rev Earth Planet Sci 33, 531-570, 2005.