COLLISIONAL EROSION: CONSEQUENCES FOR THE YOUNG EARTH Ross W. K. Potter[1,2] and David A. Kring[1,2], [1]Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX, 77058, USA, [2]NASA Lunar Science Institute; potter@lpi.usra.edu.

Introduction: Impact cratering is a fundamental geologic process involved in the original accretion and subsequent evolution of planetary bodies throughout the Solar System. Impacts have the ability to add or remove material from their target body and, therefore, affect their target's geochemical make-up.

Geochemical studies have shown that Earth, relative to chondritic and/or solar abundances, is depleted or enriched in a number of elements. This includes: depletion in heavy halogens (Cl, Br, I) [1]; a superchondritic Fe/Mg ratio (possibly by erosion of silicates relative to metals) [2], and; a superchondritic Sm/Nd ratio [3-5]. O'Neill and Palme [2] proposed the concept of collisional erosion, whereby impact events lead to the preferential removal of Earth's enriched crustal material, to explain these geochemical signatures.

Collisional erosion of Earth is thought to have taken place during the latter stages of Earth's accretion (the giant-impact(s) phase, ≤30 to 70 Myr after Solar System formation) [2], but it may also have occurred during earlier (growth of planetary embryos) or later impact bombardment. Ultimately, collisional erosion of Earth must have taken place early in its history during the Hadean period (~4.5 to 3.8 Ga) to be consistent with the abundances modeled.

Here, using analytical methods, we assess the viability of collisional erosion as a method for removing the Earth's crust (and, therefore, producing the observed geochemical anomalies) during the Hadean period.

Methods: The impactor size-frequency distribution during Earth's accretional epoch is uncertain because evidence of those collisions has been erased. We chose to begin with a known collisional size-frequency distribution – that of the Hadean basin-forming epoch – derived from studies of the Moon [6]. It is representative of the objects hitting the Earth-Moon system from the time of the 2,500 km diameter South Pole-Aitken basin-forming event >4.3 Ga to the end of the epoch ~3.8 Ga [7]. This size distribution includes impactors up to 310 km in diameter.

To determine the fraction of impact-excavated crust that escapes Earth's gravity (V_{esc} > 11.2 km/s) during this period, we calculated the mass of material (M) ejected using an equation from [8]:

$$\frac{M(V_{esc})}{m} = 0.1398 \left[\frac{V_{esc}}{U} \left(\frac{\rho}{\delta}\right)^{\frac{4}{33}}\right]^{-1.65} \qquad (1)$$

where m is the impactor mass, U is the impactor velocity, ρ is the target density, and δ is the impactor density. Impact velocities between Earth's escape velocity (11.2 km/s) and 35 km/s were analyzed, with impactor and target densities assumed to be the same (2800 kg/m^3). The constants in Equation 1 incorporate a number of parameters, with values appropriately chosen for impacts into rock [8-11]. Equation 1 defines the mass ejected above a given velocity in terms of impactor properties; crater properties are, therefore, not significant.

The presence, volume, extent, and persistence of crustal material during the Hadean period is unknown and remains a contentious issue [12 and references therein]. We, therefore, investigated a range of crustal thicknesses (2 to 40 km) distributed over various amounts (4 to 100%) of the globe. For simplicity, it is assumed that all ejected material is crust. This is not necessarily the case for the very largest impacts; ejection fractions are, therefore, upper estimates.

Results: Figure 1 plots the fraction of crustal material ejected above V_{esc} as a function of crustal thickness for a range of impact velocities and our assumed impactor size-frequency distribution. The solid square dataset shows that even impacts into a thin (2 km) crust at a very high (for Earth) impact velocity (35 km/s) remove less than 8% of the crust, assuming complete global crustal coverage (5.1x10^8 km^2).

If the crustal volume was smaller and only covered 40% of the Earth's surface (2.04x10^8 km^2 - like today), then the fraction of crust ejected increases (open squares in Figure 1). The most favorable scenario (35 km/s impact velocity, 2 km thick crust) yields ~17% crustal removal.

If the crustal volume was even smaller, covering only 2.04x10^7 km^2 (4% of Earth's surface) while maintaining the same 2 km crustal thickness, impacts at velocities greater than 22 km/s would remove >80% of the crust. However, if the crust was at least 10 km thick, no more than 35% of the crust would be removed in this scenario.

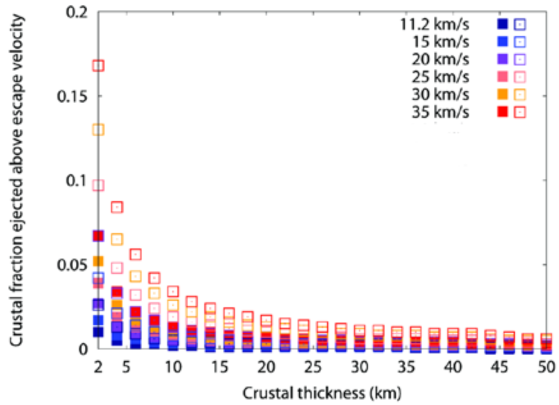

Figure 1: Fraction of crust ejected above Earth escape velocity as a function of crustal thickness for a range of impact velocities for our Hadean impactor size-frequency distribution. Solid squares assume a crustal surface area of $5.1x10^8$ km^2 (Earth's entire surface); open squares assume a crustal surface area of $2.04x10^8$ km^2 (40% Earth surface coverage).

Discussion: In general, the calculations suggest it is difficult for collisional erosion to explain the geochemical anomalies. The work of [2] requires the removal of crustal material with a mass equivalent to 1.4% of Earth's mass and, therefore, a volume of $\sim 10^{10}$ km^3. None of our modeled scenarios removed more than $\sim 10^9$ km^3.

Several factors can enhance crustal stripping: a higher impact velocity, a higher impact flux, larger impactors, or a higher volume of crust in an ideal location to be removed by a single impact. Our calculations already involve fairly high velocities (those of comets), even though evidence suggests asteroids with lower velocities of ~18 km/s were involved during the final portion of the basin-forming epoch [13]. Moreover, [13] suggest impact velocities were about half that on the Moon during the early phase of the basin-forming epoch, implying values closer to the minimum of 11.2 km/s for Earth, making crustal removal difficult. Models of the Moon-forming giant impact also favor velocities limited to 4 to 20 km/s (e.g., [14,15]).

A 10x greater impact flux with the impactor distribution of [6] and maximum impactor diameter of 500 km could also remove far more crustal material: ~65% of a 2-km thick crust is ejected in the most favorable scenario assuming entire global crustal coverage. At 40% coverage, >80% of the crust would be removed for a 2 km thick crust at velocities >23 km/s. That impact flux, however, is not consistent with observed crater densities on the Moon and would have had to occur prior to the observed basin-forming epoch.

We need to further evaluate the possibility of larger (>300-500 km diameter) impactors.

It is also possible to have all crustal material, if concentrated in a small area, removed by a single impact. For example, if 10^{10}-10^{11} km^3 of crust had formed prior to the hypothesized Moon-forming giant impact (i.e., within 30 to ~100 Myr of Solar System formation [16]) and was the focal point of the giant impact, then this event may have excavated the entire crustal volume based on a recently suggested scenario [15].

Our initial calculations do not rule out the collisional erosion model, but it may be challenging to find a plausible set of model conditions that work. That may leave us with several other potentially uncomfortable explanations for the geochemical observations: that there is a hidden, as yet undetected, reservoir within Earth that accounts for the geochemical discrepancies; that the anomalies are not really anomalies - we have, instead, been misled because Earth is not composed entirely of material represented in the current meteorite population; that the anomalies are not real because they are, instead, interpretive artifacts (e.g., [17]); or collisional erosion of crustal elements occurred on differentiated planetesimals before they accreted to Earth [18].

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References: [1] Sharp, Z. D. and Draper, D. S. (2013) *EPSL*, 369-370, 71-77. [2] O'Neill, H. St. C. and Palme, H. (2008) *Phil. Trans. R. Soc.*, 366, 4205-4238. [3] Boyet, M. and Carlson, R. W. (2005) *Science*, 309, 576-581. [4] Armytage, R. M. G. and Brandon, A. (2013) *LPSC XLIV*, #1708. [5] Campbell, I. H. and O'Neill, H. St. C. (2012) *Nature*, 483, 553-558. [6] Abramov, O. et al. (2013) *Chemie der Erde*, 73, 227-248. [7] Morbidelli, A. et al. (2012) *EPSL*, 355-356, 144-151. [8] Housen, K. R. and Holsapple, K. A. (2011) *Icarus*, 211, 856-875. [9] Housen, K. R. et al. (1983) *JGR*, 88, 2485-2499. [10] Schmidt, R. M. and Housen, K. R. *(1987) Int. J. Impact Eng*., 5, 543-560. [11] Holsapple, K. A. (1993) *Ann. Rev. Earth Planet. Sci*., 21, 333-373. [12] Harrison, T. M. (2009) *Ann. Rev. Earth Planet. Sci.*, 37, 479-505. [13] Marchi, S. et al. (2012) *EPSL*, 325-326, 27-38. [14] Canup, R. M. (2012) *Science*, 338, 1052-1055. [15] Ćuk, M. and Stewart, S. T. (2012) *Science*, 338, 1047-1052. [16] Elkins-Tanton, L. T. (2012) *Ann. Rev. Earth Planet. Sci.*, 40, 113-139. [17] Sprung, P. et al. (2013) *EPSL*, 380, 77-87. [18] Weidenschilling, S. J. et al. (2001) *Earth, Planets Space*, 53, 1093-1097.