TESTING THE COLLISIONAL EROSION HYPOTHESIS FOR THE HADEAN EARTH

Ross W. K. Potter[1,2,3] and David A. Kring[2,3], [1]Dept. Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, 02912, USA, [2]Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX, 77058, USA, [3]NASA Solar System Exploration Research Virtual Institute; ross_potter@brown.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 in heavy halogens (Cl, Br, I) [1]; has 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.

To be consistent with the abundances modeled, collisional erosion of Earth, if it occurred, must have taken place early in its history during the Hadean period (~4.5 to 3.8 Ga). O'Neill and Palme [2] suggest collisional erosion could have either (i) stripped refractory lithophile element (RLE)-rich crust from planetesimals that then accreted to form the Earth or (ii) stripped RLE-rich crust from an initially chondritic Earth during the final stages of accretion. Current data allow a fairly well constrained test of scenario (ii) relative to scenario (i). Here, therefore, analytical methods are used to assess removal of Earth's crustal material from the time of the proposed Moon-forming impact through the end of the Late Heavy Bombardment (LHB) when impacts were sufficiently large to potentially erode significant amounts of crust.

Methods: We test the collisional erosion model with four plausible impactor size-frequency distributions (SFDs) derived from examining crater size distributions on the Moon [6]. The lunar crater size distributions imply impactor SFDs similar to that among main belt asteroids [6,7], whose flux can then be scaled from the Moon to the Hadean Earth [8,9]. These size distributions include impactors up to, nominally, 1000 km in diameter.

To determine the fraction of impact-excavated crust that escapes Earth's gravity (V_{esc} > 11.2 km/s) during the Hadean, the mass of material (M) ejected was calculated using an equation from [10]:

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

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 (3000 kg/m^3). The constants in Equation 1 incorporate a number of parameters, with values appropriately chosen for impacts into rock [10-13]. 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 [14 and references therein]. Here, the mass of crust was defined as a fraction of the silicate Earth mass (4x10^{24} kg). To be consistent with previous studies [2,15] crustal mass fractions of 0.002 (similar to Earth's oceanic crust today) to 0.08 (a suitable value for the lunar crust) were considered. As with [2], a basaltic crust was assumed.

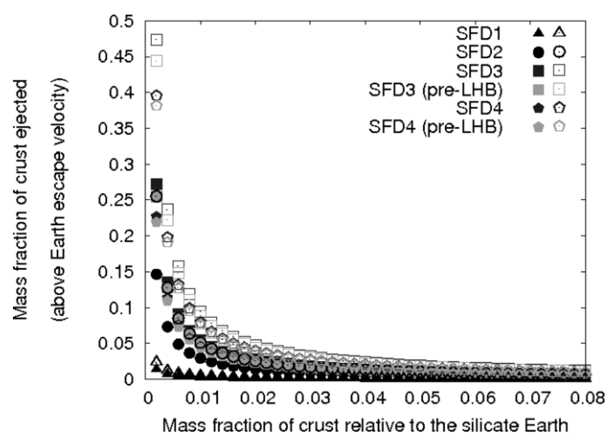

Figure 1: Mass fraction of crust ejected above Earth escape velocity as a function of crustal mass fraction relative to the silicate Earth for 25 km/s (solid symbols) and 35 km/s (open symbols) impact velocities.

Results: Figure 1 plots the mass fraction of crustal material ejected above V_{esc} as a function of mass fraction of crust relative to the silicate Earth for two sets of impact velocities (solid symbols: 25 km/s; open symbols: 35 km/s) for the four impactor SFDs. The results demonstrate that the higher the impact velocity, the greater the crustal fraction ejected above escape velocity. Size-frequency distributions 3 and 4 are divided into total and pre-LHB populations. These illustrate that the vast majority of crustal material for these respective distributions (>95%) is removed from Earth prior to, rather than during, the LHB.

Discussion: Removal of a greater percentage of crustal material prior to, rather than during, the LHB is a consequence of the greater number and size of impactors in the early Hadean. No SFD, however, removed more than 50% of the crust. The total percentage of crust ejected could be increased by considering very large (albeit low probability) impactors that were present during this time (up to 4000 km in diameter [9]). Figure 2 illustrates the outcome with one of the SFDs supplemented by a 2000, 3000, or 4000 km diameter impactor. This demonstrates that the addition of one very large impactor can help this SFD remove enough crustal mass to be consistent with the chemical constraints of collisional erosion scenarios [2,15]. The successful scenarios, though, require impact velocities of >25 km/s, which are possibly greater than the average impact velocities prior to the LHB (11 km/s [7]).

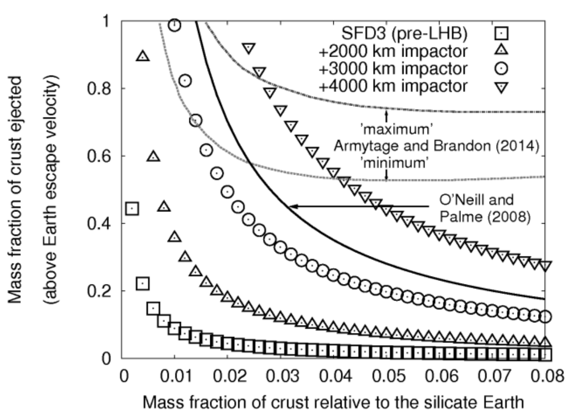

Figure 2: Mass fraction of crust ejected above Earth escape velocity as a function of crustal mass fraction relative to the silicate Earth for SFD3 supplemented by one 2000, 3000, or 4000 km diameter impactor (all impacts at 35 km/s). Data points that plot along or above the data from O'Neill and Palme [2] and Armytage and Brandon [15] represent successful collisional erosion scenarios, where enough crustal mass has been removed to satisfy geochemical constraints.

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 ~10^{10} km^3. If this crustal volume covered Earth's entire surface it would be equivalent to a global crustal layer 70 km thick. Estimates of crustal thicknesses in the Hadean, however, range from ~20-40 km [e.g., 16]. Thus, the model only works if that volume was removed serially via multiple impacts.

Geographical distribution of crust will also heavily influence its removal. If all crustal material was concentrated in a single area, it could potentially be removed by a single impact, such as scenarios recently suggested for the proposed Moon-forming impact [17]. Additionally, if any continental crust was present on the Hadean surface, removal of a given volume of this would alter Earth's geochemical to a greater extent than the same volume of basaltic crust due to its enrichment in a number of RLE [18].

Conclusions: Collisional erosion during the Hadean is a viable mechanism to explain Earth's observed geochemical signatures only if certain dynamical considerations are met. It requires an impactor size-frequency distribution containing at least one very large (>2000 km diameter) impactor and average impact velocities >25 km/s. The vast majority of crustal material would likely have been removed prior to the Late Heavy Bombardment if those dynamical constraints existed.

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] Strom, R. G. et al. (2005) *Science*, 309, 1847-1850. [7] Marchi, S. et al. (2012) *EPSL*, 325-326, 27-38. [8] Abramov, O. et al. (2013) *Chemie der Erde*, 73, 227-248. [9] Marchi, S. et al. (2014) *Nature*, 511, 578-582. [10] Housen, K. R. and Holsapple, K. A. (2011) *Icarus*, 211, 856-875. [11] Housen, K. R. et al. (1983) *JGR*, 88, 2485-2499. [12] Schmidt, R. M. and Housen, K. R. (*1987) Int. J. Impact Eng.*, 5, 543-560. [13] Holsapple, K. A. (1993) *Ann. Rev. Earth Planet. Sci.*, 21, 333-373. [14] Harrison, T. M. (2009) *Ann. Rev. Earth Planet. Sci.*, 37, 479-505. [15] Armytage, R.M.G. and Brandon, A. (2014) *LPSC XLV*, #1883. [16] van Thiesen, P. et al. (2004) *Phys. Earth Planet. Int.*, 142, 61-74. [17] Ćuk, M. and Stewart, S. T. (2012) *Science*, 338, 1047-1052. [18] Taylor, S. R. and McLennan, S. M. (1985) *The continental crust: its composition and evolution*, Blackwell, Oxford.