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The terrestrial late veneer from core disruption of a lunar-sized impactor

H. Genda [a], R. Brasser [a,1], S.J. Mojzsis [b,c,*,1]

[a] Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
[b] Department of Geological Sciences, University of Colorado, UCB 399, 2200 Colorado Avenue, Boulder, CO 80309-0399, USA
[c] Institute for Geological and Geochemical Research, Research Center for Astronomy and Earth Sciences, Hungarian Academy of Sciences, 45 Budaörsi Street, H-1112 Budapest, Hungary

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ABSTRACT

Overabundances in highly siderophile elements (HSEs) of Earth's mantle can be explained by conveyance from a singular, immense ($D \sim 3000$ km) "Late Veneer" impactor of chondritic composition, subsequent to lunar formation and terrestrial core-closure. Such rocky objects of approximately lunar mass (~ 0.01 $M_\oplus$) ought to be differentiated, such that nearly all of their HSE payload is sequestered into iron cores. Here, we analyze the mechanical and chemical fate of the core of such a Late Veneer impactor, and trace how its HSEs are suspended – and thus pollute – the mantle. For the statistically most-likely oblique collision ($\sim 45°$), the impactor's core elongates and thereafter disintegrates into a metallic hail of small particles (~ 10 m). Some strike the orbiting Moon as sesquinary impactors, but most re-accrete to Earth as secondaries with further fragmentation. We show that a single oblique impactor provides an adequate amount of HSEs to the primordial terrestrial silicate reservoirs via oxidation of ($<$m-sized) metal particles with a hydrous, pre-impact, early Hadean Earth.

1. Introduction

Highly siderophile elements (HSE), which include the platinum-group elements (Os, Ir, Ru, Rh, Pt, Pd), as well as Au, and Re, are depleted in the Earth's mantle relative to chondrites (e.g. Becker et al., 2006). This is the expected outcome because as metallic cores grow within large and differentiated planetary embryos, HSEs should be effectively stripped from silicate mantles via strong metal–silicate partitioning of the metal component into metal phases; these then become segregated into the growing metallic cores. Yet, oddly, the abundances of these metals are far greater than what is predicted by high-pressure and high-temperature experiments for partitioning of HSEs between liquid metal and silicate (e.g. Mann et al., 2012; Rubie et al., 2015a, 2015b and references therein). Adding to this riddle, the relative abundances of HSEs in the terrestrial mantle – and that of Mars (Brasser and Mojzsis, 2017) – are nearly chondritic despite their significantly different silicate-metal partitioning coefficients.

Hence, the observed HSE signature in the Earth's mantle is in conflict with the widely-held expectation that these elements should have been removed from the mantle during core formation (Kimura et al., 1974). To account for this observation, it was already proposed long ago that a relatively small augmentation (~ 1 wt%) of material enriched in HSEs was supplied late to the Earth's mantle after core formation was complete, in the form of a "Late Veneer" or LV (Chou, 1978; Rubie et al., 2016; Frank et al., 2016 and references therein). This exogenous explanation for Earth's mantle HSE signature is, however, not unanimously accepted, and debates with alternative scenarios are on-going (Willbold et al., 2011; Touboul et al., 2012; Puchtel et al., 2014; Touboul et al., 2014; Willbold et al., 2015; cf. Righter et al., 2015).

Several theories have been advanced to explain the source of the putative LV impactor(s): chondritic material supplied from the asteroid belt (Drake and Righter, 2002), leftover planetesimals from terrestrial planet formation that originated near Earth's orbit (Raymond et al., 2013), and fragments dispersed onto heliocentric orbit during a phase of giant impacts that created Earth and Venus from Mars-sized protoplanets (Genda et al., 2017a). It is noteworthy that recent data are consistent with an inner solar system origin of the LV object(s) (Fischer-Gödde and Kleine, 2017). If the LV was accreted in chondritic proportions, the total supplementary mass to Earth can be estimated at 0.5–0.8 wt%,

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[*] Corresponding author at: Department of Geological Sciences, University of Colorado, UCB 399, 2200 Colorado Avenue, Boulder, CO 80309-0399, USA.
E-mail address: mojzsis@colorado.edu (S.J. Mojzsis).

[1] Collaborative for Research in Origins (CRiO), The John Templeton Foundation – FfAME Origins Program.

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(Walker, 2009; Day et al., 2016). For clarity and consistency with previous work (Brasser et al., 2016; Brasser and Mojzsis, 2017), we refer to mass added to the inner planets after the Giant Impact that formed the Moon (ca. 4.51 Ga) and the intervening time assigned by us to the LV epoch (between ca. 4.51 Ga and ca. 4.4 Ga) with the generic expression "late accretion".

In stark contrast to Earth, HSEs in the lunar mantle appear to indicate that the Moon acquired only an additional 0.02–0.035 wt% (Day and Walker, 2015; Kruijer et al., 2015). Based on this observation, the ratio of the accreted mass between Earth and the Moon is tentatively taken to be 1950 ± 650, which is two orders of magnitude higher than the ratio of their gravitational cross sections. Several studies have attempted to explain this extraordinarily high ratio. Bottke et al. (2010) proposed that the size-frequency distribution of the remaining planetesimals from planet formation had to have been shallow even at larger diameters in excess of $\sim$1000 km. They further proposed that most of the mass delivered to the Earth should have come from a few large objects comparable in size to asteroid 1Ceres ($\sim$945 km diameter), or more statistically likely, from a larger solitary object. With only a few such entities dwelling in the inner Solar System at that time, the Moon can statistically avoid accretion of large objects while the Earth did not (Sleep et al., 1989).

The effect of such a shallow size-frequency distribution was investigated in more detail by Brasser et al. (2016). Through a combination of N-body and Monte Carlo simulations, they concluded that a single lunar-sized body striking the Earth between the final giant impact event that created our Moon at ca. 4.51 Ga (Barboni et al., 2017 and references therein), and the last major terrestrial differentiation event that separated the silicate reservoirs at ca. 4.45 Ga (e.g. Allègre et al., 2008), can account for the HSE excess in the Earth's mantle. More recently, Brasser and Mojzsis (2017) also show that it is statistically unlikely that the Moon and Mars experienced an impact as large as Earth's to explain their respective HSE supplies, which as previously mentioned comports with the very low lunar HSE abundance compared to Earth (Day and Walker, 2015) and the relatively modest martian abundances (Day et al., 2016).

Like asteroid 4Vesta (525 km diameter) and some parent bodies of the iron meteorites, a lunar-size body is expected to be differentiated depending on its formation timescale (e.g. Lee and Halliday, 1997) which means almost all its HSEs are already partitioned into an iron core. It makes sense to understand further how core materials in such objects behave under various impact conditions. How are HSEs, sequestered in an impactor's core, able to pollute the terrestrial mantle and stay suspended there (Maier et al., 2009; Frank et al., 2016) rather than immediately sink to Earth's core (Stevenson, 1981)? If the impactor's core simply merges with the Earth's core, the impactor is unlikely to supply any HSEs to the Earth's mantle since little or no interaction with silicate reservoirs (crust and/or mantle) would occur (Dahl and Stevenson, 2010).

Here, we report on our investigations of the fate of the iron core of a lunar-sized planetary embryo[2] striking the early Hadean (pre-4.4 Ga) Earth that can account for the Late Veneer hypothesis. We test the premise that the impactor's core is temporarily ejected and thereafter sheared and fragmented into small particles that descend as hail of molten iron in the post-impact phase. This scenario leaves open the possibility of supplying (and suspending) HSEs to Earth's mantle via oxidation reactions by a primordial surface hydrosphere (Abe, 1993) and/or a relatively high oxygen fugacity fayalite+magnetite+quartz (FMQ)-buffered early Hadean mantle (Trail et al., 2011).

Our study involved impact simulations as well as examination of the post-collision evolution of the impactor's core materials with a postulated early Hadean Earth's hydrosphere and mantle. In Section 2 we describe our numerical methods and explain the outcome of the collision simulations. In Section 3 we test the degree to which the impactor's core is expected to accrete onto the Moon with the aid of N-body simulations. A discussion in Section 4 presents our observations of the outcomes of our model runs and Section 5 reports our conclusions.

2. Impact simulations

Our simulations considered a lunar-sized impactor that struck the Earth under different impact angles in the period of late accretion for which previous mass and velocity analyses were reported (Brasser et al., 2016). In our model, we assumed that both Earth and the impactor are differentiated so that almost all of their HSE complements are already partitioned into their respective iron cores. We discuss the fate of the impactor's disrupted metallic core during a subsequent re-impact stage onto the Earth.

2.1. Numerical methods

To perform our impact simulations, we use the smoothed particle hydrodynamics (SPH) method (e.g. Monaghan, 1992), which is a flexible Lagrangian method of solving hydrodynamic equations. Our numerical code is the same as that reported in Genda et al. (2015a). Our code can calculate a purely hydrodynamic flow with no material strength. The shock-induced pressure in our numerical setting described below is above 200 GPa, which is much higher than the Hugoniot elastic limit for typical rocks and iron ($<$10 GPa, e.g., Melosh, 1989). Thus, the assumption with no material strength is valid.

The masses of the target (Earth) and impactor were set to be 1 $M_\oplus$ ($= 6.0 \times 10^{24}$ kg, the Earth mass) and 0.01 $M_\oplus$, respectively. As mentioned above, both the target and projectile are differentiated in our models. We further assume both objects have a 30% iron core and 70% silicate mantle by mass. According to recent detailed isotopic analysis of the Earth and meteorites, the accreted materials during the very last stage of the Earth's formation (i.e., LV) would be dominantly composed of enstatite chondrites (Dauphas, 2017). Owing to the fact that enstatite chondrites contain about 30 wt% iron in the reduced form (e.g., Wasson and Kallemeyn, 1988), a 30% iron core is considered for an impactor in our simulations. For the equation of state (EOS), we used the Tillotson EOS (Tillotson, 1962), which has been widely applied in other previous studies including planet- and planetesimal-sized collisional simulations (e.g. Canup and Asphaug, 2001; Citron et al., 2015). We used the parameter sets of basalt for the mantle and iron for the core (Benz and Asphaug, 1994, 1999).

The von Neumann–Richtmyer-type artificial viscosity was introduced as a hydrodynamics solver to capture shock waves (Fukuzaki et al., 2010; Genda et al., 2015b, 2017b). Conventionally, all SPH particles in our simulations have the same mass and the total number of particles used for the target and impactor was fixed at 10^6 and 10^4, respectively. The mass of each SPH particle is 6.0×10^{18} kg, which corresponds to 160 km and 100 km in diameter for solid (or liquid) basalt and iron, respectively. We used 1×10^5 J/kg for the initial specific internal energy for both impactor and target. We calculate all impact simulations for 10^5 sec ($\sim$1 day), and it takes about two weeks to perform one impact simulation with 16 cores. We considered no spin for pre-impact objects. Because the surface velocity of the spinning impactor and

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[2] We propose that the Late Veneer object be named *Moneta* after the Roman goddess of memory and protectress of funds (money). Alternatively, in the Greek pantheon her name is *Mnemosyne*, a Titaness and the daughter of *Uranus* and *Gaia*. The rationale behind this proposal is that the Late Veneer event should neither be conflated with the Moon-forming event (by an object dubbed *Theia*), nor with the purported "late heavy bombardment".