Earth and Planetary Science Letters 449 (2016) 96–104

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Massive impact-induced release of carbon and sulfur gases in the early Earth's atmosphere

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ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form 30 March 2016
Accepted 22 May 2016
Available online 7 June 2016
Editor: C. Sotin

Keywords:
early earth
asteroid impacts
faint young Sun
earth's atmosphere

ABSTRACT

Recent revisions to our understanding of the collisional history of the Hadean and early-Archean Earth indicate that large collisions may have been an important geophysical process. In this work we show that the early bombardment flux of large impactors (>100 km) facilitated the atmospheric release of greenhouse gases (particularly CO_2) from Earth's mantle. Depending on the timescale for the drawdown of atmospheric CO_2, the Earth's surface could have been subject to prolonged clement surface conditions or multiple freeze-thaw cycles. The bombardment also delivered and redistributed to the surface large quantities of sulfur, one of the most important elements for life. The stochastic occurrence of large collisions could provide insights on why the Earth and Venus, considered Earth's twin planet, exhibit radically different atmospheres.

1. Introduction

Atmospheric and surface conditions during the first billion years of Earth's history are poorly understood due to the paucity of geological and geochemical constraints. Early atmospheric models (Sagan and Muller, 1972; Owen et al., 1979; Kasting et al., 1984) indicated that the Earth could have been in a frozen state for hundreds of millions of years due to the reduced luminosity of the young Sun, which was approximately 20–30% less intense than today at visible wavelengths. However, the oldest terrestrial zircons dating back to ~4.3–4.4 Gyr ago hint at protoliths that interacted with liquid water at or near the surface of the Earth (Wilde et al., 2001; Mojzsis et al., 2001; Cavosie et al., 2005) based on deviation of stable oxygen isotope ratios (δ^{18}O) from mantle values. Additional support for the presence of surface or sub-surface liquid water is provided by the presence of muscovite and quartz inclusions in Hadean zircons, consistent with "S-type" granites formed from melting sedimentary protoliths including clays (Hopkins et al., 2010). In addition, chert δ^{18}O signatures (e.g., Blake et al., 2010) and the lack of glacial deposits prior to ~3 Gyr ago (Young et al., 1998) have also been interpreted as evidence against snowball conditions in the early to mid-Archean. The apparent inconsistency between theoretical climate predictions and the rock record is referred to as the faint young Sun paradox (Sagan and Mullen, 1972).

The available Hadean zircon record, however, is sparse. For instance, the age of Hadean zircons is known with a typical error (1-σ) of 5–10 Myr, while their δ^{18}O vs. age distribution is characterized by gaps of several 10s Myr. The latter may be due to bias sampling and low number statistics, nevertheless current data are consistent with episodic or prolonged periods with liquid surface water and alteration of crustal material (Cavosie et al., 2005), or, perhaps, aqueous alteration beneath a global ice shell that might experience intermittent melting (Zahnle, 2006). Alternatively, Hf, Pb, O and Nd data have been interpreted as evidence that many of the observed Hadean zircons younger than ~4.3–4.4 Gyr ago are due to the melting of older mafic crust (Kemp et al., 2010), and therefore do not require protracted clement surface conditions.

In this work, we assess the consequences of large impacts for Hadean and Eoarchean climate and surface conditions. The bombardment of the Earth by the debris of planet formation during the so-called late accretion from 4.5 Gyr ago to 3.5 Gyr ago, i.e. encompassing the Hadean and early Archean eons, was likely characterized by a plethora of large collisions (Marchi et al., 2014). Planetesimals exceeding 100 km in diameter pummeled the early Earth for hundreds of Myr, resulting in large volumes of melt produced both by immediate depressurization and by subsequent mantle convection driven by the impact (Elkins-Tanton and Hager, 2005; O'Neill et al., 2016). This buoyant melt would spread on the

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http://dx.doi.org/10.1016/j.epsl.2016.05.032

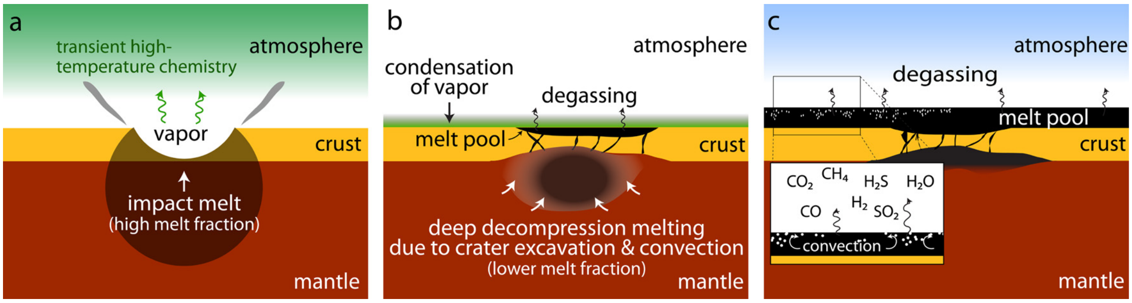

Fig. 1. Schematic cross section through an impact-generated melt pool and subsequent outgassing. a: A large impact results in the formation of a transient, silicate-rich high temperature atmosphere, prior to impact-generated melt spreading. b: Upon fast cooling ($\sim 10^3$ yr or less), the transient atmosphere condenses, while deep-seated, impact-generated melt spreads on the surface. c: As the impact-generated melt spreads, it releases gases. The outgassing indicated in panel c is expected to take place largely after the transient silicate vapors have condensed.

surface, a process further aided by the lack of significant surface topography due to a much warmer crust.

Impact-generated mantle melting and magmatism cannot be observed in the current terrestrial record due to the paucity of giant impacts. For example, the 1.85 Ga Sudbury structure is one of the largest extant impact structures on Earth (Grieve, 1987). However, the Sudbury impact (with a projectile size of ∼12 km) was much smaller than the collisions we consider here. The granitic and noritic Sudbury impact melt sheet likely derived from melting of crustal and supracrustal protoliths (Zieg and Marsh, 2005). In contrast, we expect magma generation during the larger collisions that took place during late accretion to be dominated by mantle melting.

Large igneous provinces may thus provide a more valid geological analogy, albeit without the near-instantaneous melting expected for impact-derived melt bodies. One key difference, however, is the volume of molten rocks. The largest known igneous provinces, such as the Ontong-Java Plateau, have an estimated volume approaching 10^7 km^3 (Ross et al., 2005). For comparison, the volume of mantle-derived melt generated by a collision with a 100 km asteroid exceeds 10^7 km^3, while for a 1000 km impactor it approaches 10^9 km^3 (Marchi et al., 2014).

Outgassing of volatiles (such as CO_2, SO_2, CO, and H_2S) during the emplacement of large igneous provinces is thought to have significant—although transient—repercussions for atmospheric composition, surface temperatures, ocean chemistry, and planetary habitability (e.g., Self et al., 2014; Black et al., 2014). Likewise, the emplacement of large bodies of melt on the early Earth's surface could have resulted in voluminous outgassing. However, previous work on the effects of asteroidal bombardment on the early Earth's atmosphere (e.g., Sleep and Zahnle, 2001; Zahnle et al., 2007, 2010) or more recent terrestrial impacts (e.g., Kring et al., 1996) have chiefly considered impact-vaporized materials, instead of degassing from pools of impact-generated magma. Large-scale collisions also have the potential to drastically alter the composition and temperature of a pre-existing atmosphere by releasing significant amounts of silicate vapor. Such hot, transient atmospheres are estimated to cool off and precipitate quickly: on a time scale of a few months for the silicate to condense, and $\sim 10^3$ yr for the water to rain out (e.g., Sleep and Zahnle, 1998; Zahnle et al., 2007, 2010). On longer timescales, however, melt outgassing likely dominated the budget of released gases by virtue of the much larger melt volume compared to vapor volume (see Supplementary Information).

2. Impact-generated outgassing on the Hadean Earth

To investigate the environmental effects of large collisions on the early Earth we developed a model that combines the asteroidal bombardment flux with the quantities of gas released by the resulting impact-generated melt pools (Fig. 1). In our simulations we consider impactors larger than 10 km in diameter randomly generated using the main belt asteroid size-frequency distribution extrapolated to larger sizes to account for the budget of terrestrial highly siderophile elements (Marchi et al., 2014; see their Fig. 1). The time frame of interest is 3.5–4.5 Gyr, the latter being the assumed formation time of the Moon, although our results do not depend on the absolute time of the Moon's formation. The nominal impact flux is derived using an example of a successful simulation, as shown in Marchi et al. (2014). We also tracked the stochastic variability of large collisions by using $\sim 10^3$ simulations: the number of impactors ranges from 100–150 and 10–30, respectively for impactor size larger than 100 and 200 km (Fig. S1). As described in Marchi et al. (2014) (Fig. 1a), for each collision we estimated the volume of impact-generated melt by comparing the mantle solidus with pressure and temperature fields predicted from hydro-code simulations. We adjusted our estimates to account for thermally triggered mantle convection and subsequent decompression melting based on results from Elkins-Tanton and Hager (2005). The estimated melt volumes, which depend on the assumed background potential temperature of the mantle (Marchi et al., 2014), are used as inputs for our outgassing computations (Fig. 1b). The degassing efficiency will depend on volatile concentrations in the melt, degree of melting, solubility, and speciation (Fig. 1c). The latter is controlled by the oxygen fugacity of the lower crust and mantle, which is the source material for the impact-generated melt. Despite a developing consensus that the Hadean mantle and surface environments were relatively oxidizing (e.g., Kasting, 2014), some geological evidence points to more reducing conditions (e.g., Yang et al., 2014). Therefore we tracked the production of gases in two end-member scenarios for oxidizing and reducing conditions, with and without additional volatiles from the projectiles, and with a range of Hadean mantle concentrations (see Supplementary Information). Given the uncertainties in the above factors, our strategy is to develop a baseline model for each end-member scenario. Our baseline models are tailored to describe lower limit cases, and they are characterized by conservative assumptions for outgassing throughout. The major species in the gas phase under oxidizing magmatic conditions will be CO_2 and SO_2, as in modern basalts (e.g., Trail et al., 2011). The major species in the gas phase under reducing conditions will be CO, and to a lesser extent CH_4 and H_2S (Iacono-Marziano et al., 2012; Yang et al., 2014; Kasting, 2014). In addition to the species above, it is expected that significant volumes of water vapor and H_2 were also released, although we do not specifically address them in this work.

2.1. *Hadean Earth's volatile budget*

We assume that little silica-rich continental crust existed in the Hadean, and furthermore our simulations suggest that for large Hadean impacts most melt derived from the mantle rather