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Thermal effects of late accretion to the crust and mantle of Mercury

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ABSTRACT

Impact bombardment on Mercury in the solar system's late accretion phase (ca. 4.4–3.8 Ga) caused considerable mechanical, chemical and thermal reworking of its silicate reservoirs (crust and mantle). Depending on the frequency, size and velocity of such impactors, effects included regional- and global-scale crustal melting, and thermal perturbations of the mercurian mantle. We use a 3D transient heating model to test the effects of two bombardment scenarios on early (pre-Tolstojan) Mercury's mantle and crust. Results show that rare impacts by the largest ($\gtrsim$100 km diameter) bodies deliver sufficient heat to the shallow mercurian mantle producing high-temperature ultra-magnesian (komatiitic *s.s.*) melts. Impact heating leading to effusive (flood) volcanism can account for the eponymous "high-magnesium region" (HMR) observed during the MErcury Surface, Space Environment, GEochemistry Ranging (MESSENGER) mission. We find that late accretion to Mercury induced volumetrically significant crustal melting ($\leq$58 vol.%), mantle heating and melt production, which, combined with extensive resurfacing ($\leq$100%), also explains why its oldest cratering record was effectively erased, consistent with crater-counting statistics.

1. Introduction

The first geochemical measurements made by the X-Ray Spectrometer (XRS) on the MErcury Surface, Space Environment, GEochemistry, and Ranging (MESSENGER) spacecraft, coupled with geomorphological evidence, suggested the presence of ancient (>3.9 Ga corresponding to Pre-Tolstojan; Marchi et al., 2011; Werner, 2014) komatiite-like crust on Mercury (Head et al., 2011; Nittler et al., 2011). Komatiite is an extrusive magnesium-rich (MgO $\geq$18 wt.%) rock that on Earth is most often found associated with Proterozoic (2500–0.542 Ma) and older terranes extending to the Eoarchean (Arndt et al., 2008; Frank et al., 2016). Curiously, there are also rare occurrences of Phanerozoic komatiite-like basalts related with (super-)plume activity such as at the late Mesozoic (ca. 90 Ma) Gorgona Island locality in Columbia (Aitken and Echeverría, 1984), and the Permo-Triassic (ca. 270 Ma) Song Da komatiites in Vietnam (Hanski et al., 2004). It is the usual case, however, that komatiitic lavas are restricted to ancient rocks in the terrestrial record. This observation, coupled with petrological arguments and field observations, has been used to argue that komatiitic lavas were commonplace on the Archean Earth owing to the fact that mantle temperatures were higher than present (by 200 °C or more; Arndt et al., 1997). Yet, as with many other aspects of the "early Earth" record, the petrologic and geodynamic conditions for the origin and seemingly widespread emplacement of komatiites in the first half of Earth's history are disputed (Grove et al., 1999). The general, but not unanimous, consensus is that komatiite genesis on Earth is due to ultra-high temperature mantle plumes that ascend from a deep thermal boundary layer, possibly at the core-mantle boundary (CMB; Arndt, 2003).

These ostensibly rare and ancient ultramafic lavas also appear to exist on other solid bodies in the solar system: Komatiites have been proposed as an analogue for high Mg- and Fe-basalts from Gusev Crater on Mars (e.g. Bost et al., 2012), as presently erupting from volcanoes on Jupiter's moon, Io (Williams et al., 2000), and were documented to be associated with ultramafic crustal domains on Mercury (e.g. Weider et al., 2012). A lunar komatiite component was insinuated from compositional end-member mixing models of an Apollo 16 highland breccia (Ringwood et al., 1986). The exis-

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tence of komatiites on the Moon (cf. Huppert and Sparks, 1985) and Mercury would be surprising; these are the smallest and most thermally moribund worlds of the inner solar system, and if komatiites are the result of high degrees of partial melt from deep hot plumes, as has been invoked for terrestrial komatiites stated above, it is difficult to reconcile this mechanism with what we understand about the interior structure of either. Mercury's anomalously high density (5.43 $\mathrm{g\,cm^{-3}}$) coupled with other geophysical data, suggests a very shallow CMB depth of only ∼420 km (Hauck et al., 2013) and thus a core that comprises ∼60% of its volume with a correspondingly small mantle (Smith et al., 2012). The Moon is nearly the geophysical opposite of Mercury: It has an unusually low density (3.35 $\mathrm{g\,cm^{-3}}$; approaching that of Earth's upper mantle) and a core that is just about 20% of its volume; unlike Mercury, most of the Moon's volume is occupied by its mantle.

The initial observations of komatiite-type crustal regions on Mercury were upheld by subsequent higher-resolution XRS and Gamma Ray and Neutron Spectrometer (GRNS) measurements and further petrologic models (Charlier et al., 2013; Peplowski et al., 2015; Stockstill-Cahill et al., 2012; Weider et al., 2012, 2015; Van der Kaaden et al., 2017). One geochemical terrane was shown to be especially magnesium-rich, the "high-magnesium region" (HMR; Weider et al., 2015). The HMR is defined by a large, contiguous crustal domain with a [Mg/Si] ratio of >0.5; it covers ∼15% of Mercury's surface, yet is not associated with any geological or geophysical features that could point to an unequivocal origin (Frank et al., 2017). Volcanic eruptions could be facilitated by impacts (Green, 1972; Williams and Greeley, 1994), but are not necessarily initiated by them (Ivanov and Melosh, 2003; cf. Reese and Solomatov, 2006). Systematic searches through MESSENGER datasets for evidence linking the HMR to a potentially ancient impact basin led Frank et al. (2017) to conclude that it is more likely the product of rift volcanism from a chemically and thermally heterogeneous mercurian mantle, rather than a direct consequence of impact-excavated mantle material.

In this work, we investigate the thermal and mechanical consequences of impact bombardment to Mercury's crust and mantle to understand the HMR and explore the possibility that ultramafic (ultra-magnesian) melts can be generated by altering the thermal structure of the planet's mantle. Our work is thus complementary to Rolf et al. (2017) who explored how impacts affected the evolution of the Moon's internal thermal state ∼100 Myr after bombardment.

For clarity and consistency with other work, we define the interval of "late accretion" in the solar system as the time subsequent to the separation of the silicate reservoirs of the sampled inner planets (Earth and Mars) after approximately 4.5 Ga (e.g. Brasser et al., 2016 and references therein). The *late* accretion interval thus corresponds to impact processes which occurred well after the conclusion of *primary* accretion associated with the bulk of planet formation. Such late additions nevertheless induced profound chemical and mechanical modifications of solid (silicate or icy) planetary crusts for hundreds of millions of years (Melosh, 2011). Abundant lines of evidence, based primarily on lunar studies, show that shock-metamorphism – including small degrees of melting – extended into the Archean and Paleoproterozoic eons (reviewed in Bottke and Norman, 2017). Samples from the Moon show evidence for relatively late impact reset ages at ca. 3.95–3.85 Ga that correspond to estimates for the age of Imbrium basin (e.g., Hopkins and Mojzsis, 2015; Kelly et al., 2018 and references therein). The existence and nature of a late heavy bombardment (LHB) is, however, debated (cf. Boehnke and Harrison, 2016). A common interpretation of the record of late accretion is that of a superimposed LHB impactor uptick (Ryder, 1990) from what is almost certainly an overprint of the Imbrium basin-forming event (Bottke and Norman, 2017) on an otherwise extended monotonic decline of the impactor flux to the inner solar system (Dalrymple and Ryder, 1993, 1996; Tera et al., 1974; Turner et al., 1973). The duration of a proposed LHB spike, even if it is real, is also unclear and controversial, but may have lasted between 20–200 Myr (cf. Hartmann et al., 2000). Meteorites derived from multiple parent bodies in the asteroid belt, as well as the ancient martian meteorite ALH84001, further show effects of impact-induced metamorphism with some rare dates that overlap that of Imbrium cited above (e.g., Bogard, 1995; Ash et al., 1996; Kring and Cohen, 2002; Swindle et al., 2009; Marchi et al., 2013). Many have used this observation to shore up the argument for a solar system-wide LHB. Lastly, the contemporary population structure of the main asteroid belt can be explained by late-stage giant planet migration (Minton and Malhotra, 2009) as described in the popular Nice model (Tsiganis et al., 2005); the Nice model outcome has been widely invoked to explain the LHB (Gomes et al., 2005). Yet it is important to note that the absolute timing of this postulated late-stage migration is loosely constrained, with a dynamic uncertainty of at least 250 Myr (e.g., Morbidelli et al., 2012). In aggregate, although data suggest that bombardment between ca. 4.5–3.8 Ga affected the inner solar system by resurfacing or even melting substantial fractions of the terrestrial planets' crusts (Tonks and Melosh, 1993), the precise timing and intensity of this bombardment remains unclear.

We examine whether impact bombardment to Mercury's shallow mantle in its pre-Tolstojan eon could be a viable mechanism for triggering the production of komatiite-like melts at the regional scale (cf. Frank et al., 2017). To do this we assess the increased impact flux during late accretion in two bombardment scenarios, roughly coincident with strong surface modification on Mercury (Marchi et al., 2013; Werner, 2014) and determine whether this mechanism could have induced sufficient temperature increase in a peridotite mantle to enable crossing of the komatiite solidus. Explaining the genesis of such high-temperature ultra-high magnesian silicate melts contributes to our assessment of the degree of crustal melting due to sustained periods of bombardment across the inner solar system and how such resurfacing can reset crater counting statistics.

2. Model description

Considering the uncertainties in both the timing and duration of late accretion to Mercury, we analyze two bombardment scenarios: The first is the "classical Late Heavy Bombardment," (cLHB) as described in Abramov and Mojzsis (2016); second is a hybrid-LHB characterized by a brief increase in impacts followed by an extended decay over about 400 Myr ("sawtooth Late Heavy Bombardment," sLHB; Morbidelli et al., 2012; Abramov and Mojzsis, 2016; cf. Turner, 1979). We refer the reader to Fig. 1 of Abramov and Mojzsis (2016) for a representation of the time-flux evolution of these two models. Recent successors to the Nice model (Morbidelli et al., 2012; Marchi et al., 2012, 2014; reviewed in Bottke and Norman, 2017) favor the sawtooth scenario, but this too is debated (e.g., Kaib and Chambers, 2016). We reserve our models to the two general cases described above, and we assess the viability of the bombardment mechanism to heat the planet's mantle sufficiently to generate komatiite-type melts and to both thermally and mechanically modify its crust.

Using the Marchi et al. (2013) impact flux parameters for Mercury, we simulate late accretion in both a cLHB and sLHB model, following Abramov and Mojzsis (2016). It is worth mentioning that in that study, which was applied to Mars, we modeled a cLHB scenario as a spike in impactors at ca. 3900 Ma and constant flux over the subsequent 100 Myr (e.g. Abramov and Mojzsis, 2009). The cLHB scenario can also be viewed as broadly representative of the Neukum and Ivanov (1994) "classic post-accretionary" time-