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Paleo-heat flows, radioactive heat generation, and the cooling and deformation history of Mercury

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ABSTRACT

Estimates of lithospheric strength for Mercury, based on the depth of thrust faults associated with large lobate scarps (which were most probably formed previously to ∼3 Ga) or on the effective elastic thickness of the lithosphere supporting a broad rise in the northern smooth plains (whose formation is poorly constrained, but posterior to 3.8 Ga), serve as a basis for the calculation of paleo-heat flows, referred to the time when these structures were formed. The so-obtained paleo-heat flows can give information on the Urey ratio (*Ur*), the ratio between the total radioactive heat production and the total surface heat loss. By imposing the condition $Ur < 1$ (corresponding to a cooling Mercury, consistent with the observed widespread contraction), we obtain an upper limit of 0.4 times the average surface value for the abundance of heat-producing elements in the outer solid shell of Mercury. We also find that if the formation of the northern rise occurred in a time posterior to ∼3 Ga, then in that time the Urey ratio was lower, and the cooling more intense, than when most of large lobate scarps were formed. Thus, because largest lobate scarps deform older terrains (suggesting more intense contraction early in the mercurian history), we conclude that the northern rise was formed previously to 3 Ga. If the age of other smooth plains large wavelength deformations is similar, then tectonic activity in Mercury would have been limited in the last 3 billion of years.

1. Introduction

Calculation of paleo-heat flows from lithospheric strength (using as strength indicator the depth of large thrust faults or the effective elastic thickness of the lithosphere) can potentially be used in order to constrain the thermal evolution of a planetary body (e.g., Ruiz et al., 2011), because the obtained values refer to the time of deformation (i.e., the time of faulting or loading). In the case of Mercury, paleo-heat flows calculated in this way could be useful for obtaining information on the cooling history of Mercury and their geological implications. Paleo-heat flows can also be used to constrain the whole abundance of radioactive heat-producing elements (HPE) in the silicate portion of Mercury independently of specific compositional models.

The surface of Mercury exhibits numerous compressional tectonic features (e.g., Strom et al., 1975; Dzurisin, 1978; Watters et al., 2001, 2009), most probably related to planetary cooling and contraction (e.g., Strom et al., 1975). The more representative of these structures are lobate scarps, interpreted to be the surface expression of large thrust faults deforming the lithosphere down to depths of 30 or 40 km (Watters et al., 2002; Ritzer et al., 2010; Egea-González et al., 2012). Most of the large lobate scarps were probably formed during the first third of the history of the planet, because they affect mainly Calorian or older terrains (Watters et al., 2009; Watters and Nimmo, 2010), although some lobate scarps affect Mansurian or Kuiperian terrains (Banks et al., 2012). Previous works have used the deduced estimates of depth of faults beneath lobate scarps, taken as representative of the brittle–ductile transition (BDT) depth, in order to calculate the local heat flow at the time when faulting occurred (Watters et al., 2002; Nimmo and Watters, 2004; Egea-González et al., 2012).

Recently, the existence of a broad, ∼950 km in diameter, topographic rise in the northern plains of Mercury (Fig. 1) has been revealed through MESSENGER topography (Zuber et al., 2012); moreover, a high (∼70–90 km) effective elastic thickness has been derived, from MESSENGER topography and gravity, for the lithosphere supporting this rise (Smith et al., 2012). The surface appearance of the northern rise is similar to that observed across the northern plains (Fig. 2), and flooded craters around this rise have floors tilted consistently with regional slopes, suggesting that the northern plains were elevated here after their emplacement (Balcerski et al., 2012; Dickson et al., 2012); the time of loading of

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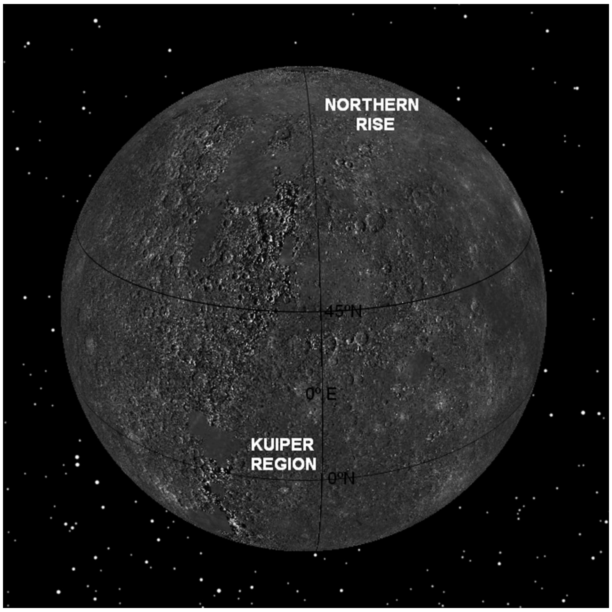

Fig. 1. Globe map of Mercury showing the location of the Kuiper region and the northern rise.

the lithosphere by the northern rise is therefore not well constrained. Similar observations have been reported for other volcanic plains, implying that large-scale topographic modifications postdated volcanic plains emplacement at 3.7–3.8 Ga (Solomon et al., 2012). Heat flows have not been calculated previously from the effective elastic thickness of the lithosphere in the northern rise, although they would give complementary information to those obtained for other regions from fault depths.

In this work, we first use heat flows derived from the BDT depth beneath lobate scarps and HPE surface abundances in order to constrain the total abundance of heat sources in the silicate fraction of Mercury. Next, we use our results for lobate scarps to constrain the calculation of paleo-heat flows from the effective elastic thickness of the lithosphere in the northern rise. Finally, we will discuss the implications of our results for the cooling history of Mercury and for the timing of large-scale topography modifications of the Calorian volcanic plains.

2. Heat flows and HPE abundance from the depth of thrust faults

Faulting depths of thrust faults associated with lobate scarps have been estimated in several cases through forward modeling procedures by using topographic profiles derived from stereoscopic Mariner 10 images (Watters et al., 2002; Nimmo and Watters, 2004), MESSENGER Laser Altimeter flyby data (Ritzer et al., 2010), or Earth-based radar surveys (Egea-González et al., 2012). In all the cases the obtained faulting depths are similar. These faulting depths can in turn be used to derive heat flows, because large faults usually deform the lithosphere down to the crustal brittle–ductile transition (BDT), which is temperature-dependent.

Here we take as representative the case of thrust faults in the Kuiper region (including Santa Maria Rupes and two unnamed lobate scarps; Figs. 1 and 3), studied by Egea-González et al. (2012), in order to calculate heat flows following the methodology described in Ruiz et al. (2009). We therefore use a BDT depth between 30 and 40 km, a surface gravity of 3.7 m s^{-2}, a surface temperature of 435 K (representative for the Kuiper region; see Vasavada et al., 1999; Aharonson et al., 2004), strain rates of $10^{-16}\,s^{-1}$ and $10^{-19}\,s^{-1}$ (which are typical values for, respectively, active terrestrial plate interiors (e.g., Tesauro et al., 2007) and for planetary thermal contraction (Schubert et al., 1988)), and the flow law of dry Maryland diabase for dislocation creep parameters (Mackwell et al., 1998). Heat flows are calculated from the temperature at the BDT depth; this temperature is obtained by equating brittle (pressure-dependent) and ductile (temperature-dependent) strength at the BDT depth. For consistency with the crustal model of Smith et al. (2012) we assume a crustal density of 3100 kg m^{-3}. We assume crustal potassium, thorium and uranium abundances (1150 ppm, 220 ppb and 90 ppb, respectively), based on surface

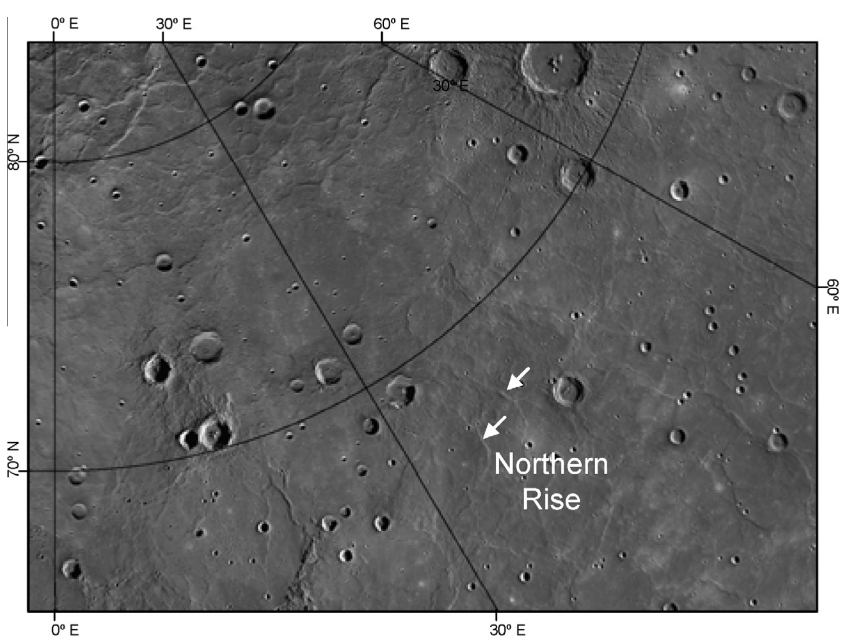

Fig. 2. MESSENGER mosaic showing a large extension of smooth plains, including the northern rise, whose approximate center is indicated by NR. The surface geology at the northern rise is non-differentiable of that of surrounding plains. Moreover, its central area is affected by several arcuate wrinkle ridges (white arrows), whose orientation pattern seem unrelated to the rise (but maybe related to a buried impact basin). Thus, surface geology suggests that the formation of the northern rise postdates plains emplacement.