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Influence of solar insolation and tidal dissipation on the global tectonics of Mercury

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Abstract

Lobate scarps on Mercury most likely result from planetary contraction but their non-random orientations cannot be explained by a completely isotropic model. Besides the deformation due to despinning, another source of anisotropy is the spatial variation of the lithospheric thickness. Solar insolation and tidal heating respectively lead to equatorial and polar thinning of the lithosphere. Both phenomena also cause a longitudinal thickness variation of lesser amplitude. We explore the effect of these mechanisms on the global tectonic pattern.

1. Introduction

With the exception of the interior of Caloris basin, nearly all tectonic features on Mercury are of compressional nature [1]. The most common of them are lobate scarps, which are interpreted as the surface expression of thrust faults. Their timing is uncertain: they formed during or after the Calorian era (3.9-3.5 Gyr), in any case after the Late Heavy Bombardment (3.8 Gyr). Their orientation is predominantly north-south, except south of 50°S where east-west faults are as common as north-south ones [2]. Since they are found all over the surface, their most likely cause is a global contraction event corresponding to a reduction in radius of 1-2 km. Global contraction however leads to faults with random orientations, at least if the lithosphere is of uniform thickness. The addition of despinning results in north-south faults, but this model has several shortcomings. First, contraction needs to be significantly larger than 2 km, otherwise strike-slip faults appear instead. Second, despinning was most likely achieved much before the Late Heavy Bombardment, thus before the formation of lobate scarps. Third, this model neither explains the east-west oriented faults in the South nor the fact that most lobate scarps are in the South [2]. Here we analyze the implications of lithospheric thickness variations on the formation of lobate scarps. We consider two phenomena affecting the lithospheric thickness, the first being the latitudinal variation in solar insolation and the second being localized tidal dissipation.

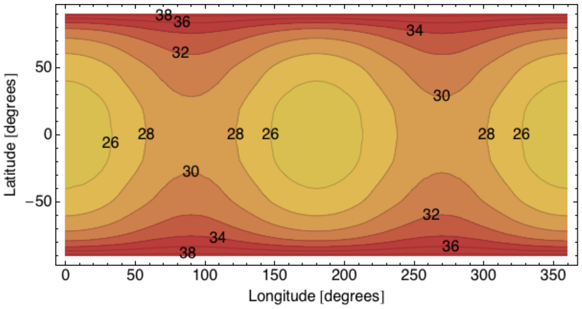

Figure 1: Effect of solar insolation on the lithospheric thickness (in km) for a uniform heat flux $F_b = 40\,\mathrm{mW/m^2}$ ($h = 100\,\mathrm{km}$, $H = 0.065\,\mu\mathrm{W/m^3}$). Mercury is in resonance 3:2.

2. Resonance 3:2

Besides the typical latitudinal variation of the solar flux, Mercury has the particularity that the mean solar insolation also depends on the longitude because of the orbital resonance 3:2 combined with the high eccentricity. A two-layer model combined with radiometric observations predicts temperatures at depth to be respectively 427 K and 325 K at the equatorial 'hot' and 'warm' poles, and less than 140 K at the north and south poles [3].

Assuming a conductive temperature profile in the crust, we compute the effective elastic thickness (see Fig. 1) by the yield-strength envelope formalism [4]. The model depends on many parameters such as the crustal thickness h and the crustal heat generation H but the ones that interest us here are the surface temperature and the basal heat flux F_b. The mean basal heat flux and the parameter H are chosen so that the brittle-ductile transition depth is 30-40 km [5].

The next step consists in solving the membrane equation on a lithosphere of variable thickness [6, 7].

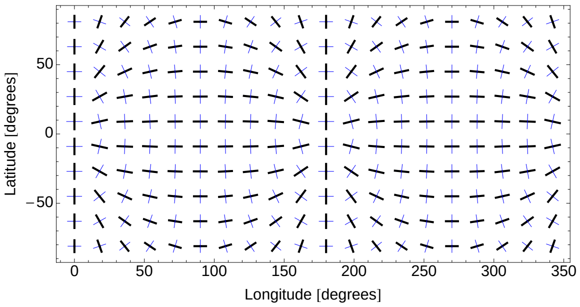

Figure 2: Orientation of faults (thick black lines) and of maximum compressive stress (thin blue lines) for global contraction on a lithosphere affected by solar insolation. Mercury is in resonance 3:2.

Once the stresses are known, the style and orientation of faults can be predicted with the help of Anderson's theory of faulting. Global contraction generates faults that are predominantly east-west (see Figure 2). This pattern is not in agreement with the north-south orientation of most lobate scarps.

What is the effect of tidal heating? The time-dependent tidal forces due to the Sun deform the planet, causing friction and heat within the body and giving rise to a non-uniform surface heat flux. However the slow orbital rotation and orbital motion of Mercury make the heat flux due to dissipation rather small at the present epoch (under $1\,\mathrm{mW/m^2}$ in most models, see [8]) so that the effect on the lithospheric thickness variation is now negligible.

Therefore, solar insolation and tidal heating effects cannot explain the orientation of lobate scarps if they formed on an intact lithosphere after the end of despinning.

3. Fast rotation

Let us now assume that the orientation of the lobate scarps is determined by a preexisting faulting network that formed before despinning was achieved [9, 10, 11]. Instead of working on the formation of lobate scarps, we thus try to find how preexisting faults could form with the right pattern.

Before despinning, Mercury initially had a much faster rotation, probably comparable to Mars and the Earth. The variation in solar insolation was zonal and led to equatorial thinning of the lithosphere. In that case, an early global contraction generates east–west thrust faults. Despinning stresses tend to align contractional faults in the north-south direction, but faults strike east-west in polar regions if (1) the lithosphere is thinner at the equator, (2) the contraction is large enough and (3) the thinner zone has a relatively large latitudinal extension [7]. This pattern fits well the orientations of lobate scarps but requires despinning stresses significantly smaller than those corresponding to an initial rotation period of 20 h commonly assumed for Mercury. Another problem is that faults preferably form in the equatorial region.

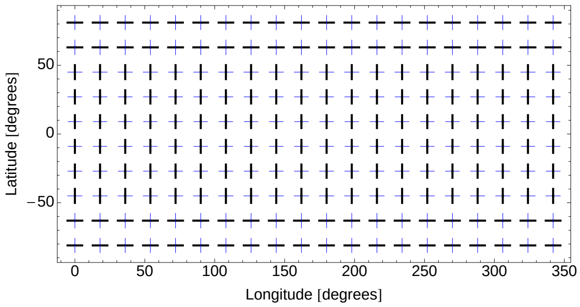

Figure 3: Orientation of faults (thick black lines) and of maximum compressive stress (thin blue lines) for global contraction on a lithosphere affected by solar insolation and tidal heating. Mercury has a fast rotation.

When Mercury rotated fast, tidal dissipation was much larger and may have had a significant effect on the lithospheric thickness. Since tidal dissipation is maximum at the poles and minimum at the equator [8], it counteracts the effect of the spatial variation in solar insolation. With a suitable choice of parameters,, tidal dissipation and solar insolation have comparable effects on the lithospheric thickness, so that the lithosphere has a maximum thickness at the equator and at the north/south poles, whereas it is of minimum thickness at intermediate latitudes. Global contraction then generates north-south faults from the equator to mid-latitudes and east-west faults in polar regions (see Figure 3). This pattern not only fits well the observed orientations but has the advantage that faults preferably form at high latitudes. Since despinning tends to change the faulting orientation from east-west to north-south, such a scenario is only possible if despinning stresses can be neglected. Either the initial rotation period was much longer than 20 h, or faulting due to despinning occurred on the faults previously created by contraction.

4. Conclusions

Though solar insolation cannot be the anisotropic component responsible for the north-south orientation of most lobate scarps, it has an important effect on the lithospheric thickness which could be crucial if MESSENGER confirms the east-west orientation of lobate scarps in polar regions. With the present-day orbit of Mercury, tidal heating has a negligible effect on the lithospheric thickness. It must however be included when considering two-stage processes, in which the tectonic pattern is imprinted during despinning and reactivated later by renewed faulting.

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