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Accommodation of lithospheric shortening on Mercury from altimetric profiles of ridges and lobate scarps measured during MESSENGER flybys 1 and 2

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ABSTRACT

The Mercury Laser Altimeter on the NASA MESSENGER mission has ranged to several ridges and lobate scarps during two equatorial flybys of the planet Mercury. The tectonic features sampled, like others documented by spacecraft imaging and Earth-based radar, are spatially isolated and have vertical relief in excess of 1 km. The profiles also indicate that the faulting associated with their formation penetrated to tens of kilometers depth into the lithosphere and accommodated substantial shortening. To gain insight into the mechanism(s) of strain accommodation across these structures, we perform analytical and numerical modeling of representative dynamic localization mechanisms. We find that ductile localization due to shear heating is not favored, given our current understanding of thermal gradients and shallow thermal structure of Mercury at the time of ridge and scarp formation, and is likely to be of secondary importance at best. Brittle localization, associated with loss of resistance during fault development or with velocity weakening during sliding on mature faults, is weakly localizing but permits slip to accumulate over geological time scales. The range of shallow thermal gradients that produce isolated faults rather than distributed fault sets under the assumption of modest fault weakening is consistent with previous models for Mercury's early global thermal history. To be consistent with strain rates predicted from thermal history models and the amount of shortening required to account for the underlying large-offset faults, ridges and scarps on Mercury likely developed over geologically substantial time spans.

1. Introduction

The manner by which a planetary lithosphere experiences contraction and the amount and timing of horizontal shortening provide important information on global thermal history. The style of deformation, brittle or ductile, bears on the thermal and mechanical structure as well as the rate of deformation. As deduced from observed deformation, strain rates coupled with the integrated record of strain provide clues to the processes and rates at which heat is generated and lost from within a planet. Whether deformation takes place in a localized (e.g., along discrete faults) or a spatially distributed (e.g., sets of faults) manner provides pertinent information on lithospheric structure and stress history. In this study we combine altimetric observations (Zuber et al., 2008a,b; Smith et al., 2010) of localized shortening across contractional ridges and lobate scarps on Mercury acquired by the Mercury Laser Altimeter (MLA) (Cavanaugh et al., 2007) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft (Solomon et al., 2008; Watters et al., 2009) with analytical and numerical models of localization processes to gain insight into the nature of strain accommodation in the planet's lithosphere.

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2. Observations of contractional tectonic features

Images from Mariner 10 (Strom et al., 1975; Melosh and McKinnon, 1988) and MESSENGER (Solomon et al., 2008; Watters et al., 2009) indicate that tectonic structures on Mercury are dominantly contractional in nature. Structural features include lobate scarps, high-relief ridges, and wrinkle ridges, with lobate scarps being the most widespread (Watters et al., 2009). Many of these structures, particularly the lobate scarps, are believed to have formed primarily in response to a decrease in planetary radius (Solomon, 1977; Solomon et al., 2008; Watters et al., 2004, 2009) that accompanied cooling of the interior over the course of the planet's evolution (Solomon, 1977; Hauck et al., 2004; Watters et al., 2004; Zuber et al., 2007). Thermal history models (Solomon, 1976, 1977, 1978, 1979; Schubert et al., 1988; Hauck et al., 2004; Dombard and Hauck, 2008) are generally consistent with the inference from the distribution of lobate scarps and their stratigraphic relations with plains units that contraction initiated prior to the end of heavy bombardment, with the oldest lobate scarps predating smooth plains emplacement and the youngest postdating the most recent plains material (Solomon et al., 2008). Contraction occurred primarily in response to interior cooling associated with the decay of heat-producing elements, but the thermal state and contractional history were also influenced by the extraction of melt from the mantle, the possible cessation of mantle convection, and the nucleation and growth of a solid inner core (Hauck et al., 2004).

The magnitude of accumulated contractional strain provides an important constraint on the thermal history models. Lobate scarp relief has been measured from Mariner 10 stereo-derived topography and Earth-based radar altimetry (Strom et al., 1975; Watters et al., 1998), and from analysis of shadow measurements on MESSENGER images (Watters et al., 2009). Estimates of horizontal shortening across individual scarps inferred from topography and from foreshortened impact craters range from <1 to 3 km (Solomon et al., 2008; Watters et al., 2009). The average areal contractional strain extrapolated globally ranges from 0.06% to 0.08% (Watters et al., 2009).

MESSENGER (Santo et al., 2001; Solomon et al., 2001, 2007) has so far executed three flybys of the planet Mercury, in January and October 2008 and September 2009. During flyby 1, MLA (Cavanaugh et al., 2007) ranged to Mercury's surface and acquired 3617 measurements along a 3200-km-long topographic profile in the equatorial region of the planet (Zuber et al., 2008a; Smith et al., 2010), mostly within the hemisphere of Mercury not imaged by Mariner 10. During flyby 2, MLA acquired 4388 ranges, again along an equatorial profile about 4000 km in length on nearly the opposite hemisphere of the planet, where Mariner 10 and MESSENGER images were available (Zuber et al., 2008b; Smith et al., 2010). No MLA observations were acquired during flyby 3 because a spacecraft safe-hold event halted instrument operations immediately prior to the planned acquisition period for MLA data, although additional images of areas profiled earlier were obtained.

Because MLA ranging to Mercury's surface has so far been restricted to these two flyby profiles, sampling of tectonic features is necessarily limited. Fig. 1 shows five ridges and scarps for which altimetry has been collected, and Table 1 notes locations and measured vertical offsets. For all the lobate scarps measured the offsets exceed 1 km, which is comparable to but at the high end of relief determined for other lobate scarps on Mercury measured from Mariner 10 stereo-derived topography and Earth-based radar altimetry (Watters et al., 1998).

Relief in excess of 1 km is also comparable to the maximum relief of a subset of lobate scarps in the vicinity of the hemispheric dichotomy on Mars (Watters, 2003). However, abundant wrinkle ridges on Hesperian-aged plains of Mars as mapped by the Mars Orbiter Laser Altimeter (Zuber et al., 1992), although similar in cross-sectional shape to the features in Fig. 1, are characterized by surface relief that is less on average by a factor of 3 or more (Golombek et al., 2001).

The most likely explanation for these ridge and scarp structures is that each represents the surface expression of a thrust or reverse fault (Strom et al., 1975; Melosh and McKinnon, 1988; Watters et al., 1998, 2002), perhaps accompanied by multiple splayed minor normal faults near the surface associated with flexural bending of near-surface strata (Plescia and Golombek, 1986; Golombek et al., 2001; Mueller and Golombek, 2004). Secondary structures within ridges and scarps that might be indicative of the complexity of subsurface faulting have not yet been identified in images from the Mariner 10 (Strom et al., 1975; Melosh and McKinnon, 1988) or MESSENGER flybys (Solomon et al., 2008; Watters et al., 2009). But if ultimately revealed by higher-resolution imaging when the MESSENGER spacecraft achieves orbit about Mercury in 2011, back thrusts in association with these structures would indicate mechanical layering of the deformed strata (Cooke and Pollard, 1997; Niño et al., 1998; Schultz, 2000; Okubo and Schultz, 2004). In the current analysis, we focus on interpretation of primary structure, particularly vertical offset. Estimation of strain from a topographic cross-section requires knowledge of the dip of the primary thrust or reverse fault and the penetration of that fault into the lithosphere. Such information is not available for Mercury, and so we limit our analysis to the interpretation of ridge and scarp relief, which is precisely measured by MLA.

Faulting can be either thin- or thick-skinned (Plescia and Golombek, 1986; Watters, 1988), reflecting the depth of fault penetration. On Mars, extensive analysis of the ridges in Lunae Planum indicates thick-skinned deformation, which implies considerable involvement of the lithosphere in faulting and sufficient strength at depth in the lithosphere to maintain conditions appropriate for faulting (Watters, 1991; Zuber, 1995).

As for Mars, the profiles of ridges and scarps on Mercury appear consistent with significant penetration of faulting into the lithosphere. Analysis of the contractional features sampled by stereo imaging (Strom et al., 1975; Watters, 1988) and MLA (Zuber et al., 2008b) indicate that the typical shortening accommodated per feature exceeds that of Martian ridges. Additionally, the areal density of such features on Mercury is considerably lower than on Mars (Watters et al., 2009; Montési and Zuber, 2003a). It appears that contractional deformation on Mercury as manifested by lobate scarps and high-relief ridges is more localized than on Mars. In this analysis we consider the implications of distributed versus localized deformation on Mercury with the intention of gaining insight into the mechanism(s) of strain accommodation.

3. Strain localization

In order to evaluate quantitatively how strain has been accommodated in Mercury's lithosphere, we apply the unified theory of strain localization (Montési and Zuber, 2002). In this formalism, dynamic localization within a planetary material of strength σ occurs via a feedback between rheology and the deformation field. In the most general sense, the rheology relates a set of state variables $\{\chi_i\}$, such as strain, strain rate, strain history, and composition, to the strength of the system through

$$\sigma = \sigma\{\chi_i\}. \tag{1}$$

A special case can be established by defining a parameter χ_o, which we refer to as the localizing quantity (Montési and Zuber, 2002). Dynamic localization of χ_o occurs if the system of internal variables adjusts to a small perturbation of χ_o in such a way that an