DESPINNING PLUS GLOBAL CONTRACTION AND THE ORIENTATION OF LOBATE SCARPS ON MERCURY.
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Introduction: Images from the three flybys of Mercury by Mariner 10 revealed a network of lobate scarps on the ~45% of the surface that was viewable; these structures are linear to arcuate, tens to hundreds of kilometers in length with relief up to a few kilometers, and are inferred to be the surface expression of large thrust faults [1]. Given the ubiquitous nature of the lobate scarps on the observed portion of the surface and the lack of extensional features, the scarps are believed to record ~1-2 km of radial contraction associated with cooling of the planet over the last ~4 Gyr (i.e., since the end of Late Heavy Bombardment [LHB]). We have previously used this range as a constraint in models of the thermomechanical evolution of Mercury, generally predicting more radial contraction over the last 4 Gyr than is observed and only satisfying the constraint for a restricted set of parameters [2].

A somewhat enigmatic observation is that the lobate scarps may be preferentially oriented N-S [3, 4]. Global contraction would produce an isotropic stress field on the surface, resulting in tectonic structures with no preferred orientation. Consequently, it has been proposed that global contraction augmented by stresses associated with despinning of the planet could yield N-S-oriented thrust faulting [5, 6]. Here, we resurrect this idea and use it to provide an additional constraint to our thermomechanical models.

Global Contraction + Despinning: Simple, thin elastic shell models of a despinning planet [e.g., 3] predict tensile stresses in polar regions, with the magnitude of the latitudinal stress exceeding the longitudinal stress such that the resultant tectonic feature would be an E-W striking normal fault. The magnitudes of the stresses are identical at the poles and become more compressive as the equator is approached. Thus, an isotropic compressive stress field (e.g., from global contraction) of sufficient magnitude would add to the despinning stresses to produce global thrust faults, oriented N-S because the longitudinal stresses would always be more compressive than the latitudinal stress. We can place a lower bound on the magnitude of the necessary decrease in planetary radius by calculating the compressive stress needed to overcome the maximum tensile stresses from despinning (i.e., at the poles) and then take the lithosphere to compressive failure.

The resultant stress field would predict stronger compressive stresses near the equator, and hence better developed lobate scarps at low latitudes. This is not observed; if anything, the lobate scarps are better expressed at high southern latitudes [4]. The despinning time scale for Mercury has been estimated to be < 1 Gyr [3]. Thus, one plausible explanation for the lack of a strong latitudinal dependence to the lobate scarps is that despinning (plus contraction) occurred prior to the end of LHB. The surface expression of the initial scarps was erased, and the presently observed scarps arose from an isotropic, global-contraction stress field that reactivated pre-existing faults, thus inheriting a preferred N-S orientation. Assuming then that despinning occurred prior to ~4 Ga, we can estimate the magnitude of an early phase of global contraction.

Mercury's current sidereal rotational period is ~59 days, down from an estimated initial period of ~20 hr [see 3]. We use measured values for the mass and mean radius of Mercury and assume a canonical value of Poisson's ratio (0.25) and a Young's modulus of 100 GPa. The amount of contraction is dependent on the strength of faults. This value has been estimated for large faults on the Earth, Mars, and Venus to span the range of ~10-80 MPa [7]. Using these values, ~3.1-4.4 km of global contraction is predicted. Allowing a reasonable 40% variation in the Young's modulus of the elastic lithosphere of Mercury expands this range to ~3-5.5 km of global contraction prior to ~4 Ga.

Thermal Model: Our approach to understanding Mercury's global contraction (or expansion) is to couple a model for the planet's internal thermal evolution to a model for the accumulation of thermoelastic strains in an elastic shell overlying an inviscid interior [see 2 and references therein for complete details]. The thermal model calculates both the convective and conductive parts of the heat lost through the lithosphere and mantle, the cooling of the core and solidification of an inner core, and the production of melt and formation of a crust. We implement a parameterized mantle convection technique, using a Rayleigh-Nusselt # relationship for fluids with strongly temperature-dependent viscosities, and modified to include the potential transition to full conduction. By employing a one-dimensional representation of convective heat transfer in a spherical shell overlying a core, coupled to a finite-element model for conduction in the lithosphere (and the mantle if convection ceases), we can calculate representative thermal evolution scenarios for the planet. Overall, planetary cooling and precipitation of a solid iron inner core result in changes in planetary volume, which are recorded in the lithosphere through an accumulation of horizontal strains. The thickness of the elastic lithosphere is defined by the depth to the 950-K isotherm.

Results: We have previously used estimates of the amount of strain recorded in lobate scarps as a constraint on the internal evolution of Mercury over the last 4 Gyr [2]. In contrast, here we estimate the amount of contraction in our thermal evolution models during the first 0.5 Gyr of the planet's history. The rate of radial contraction of Mercury due to planetary cooling depends primarily on the initial temperatures of the interior, the viscosity of the mantle, the abundance of heat producing elements, and the amount of a light, alloying element in the core. Most simulations result in comparable amounts of post-4.0 Ga global contraction in excess of the ~1-2 km currently observed in the lobate scarps, except for one suite in which the high metal-to-silicate ratio of Mercury is a product of silicate vaporization, with heat production provided only by long-lived (14-Gyr half-life) ^{232}Th.

To utilize this additional constraint of pre-4 Ga contraction of ~3-5.5 km, we have recalculated a select subset of simulations to determine the amount of strain (i.e., radial contraction) that is generated before the end of LHB. Three suites of simulations, two with heat-producing-element compositions dominated by a condensation-sequence assemblage but with differing initial interior temperatures (1800 K and 1900 K), and one with heat production constrained by a vaporization model (at 1800 K initial temperature) are calculated. Figure 1 illustrates the amount of contractional strain accumulated in the first 0.5 Gyr of the planet's history as a function of bulk core sulfur content for each of these three suites. The two simulations with initial temperatures at the base of the lithosphere of 1800 K achieve > 0.08% contractional strain (i.e., more than 2 km of radial contraction) and are virtually indistinguishable despite the > 30% higher heat production in the vaporization-based model during this period. It is also evident from Fig. 1 that the amount of global contraction is very sensitive to the initial temperatures of the interior, as an increase of 100 K leads to at least an additional 2-2.5 km of contraction.

Discussion: Our results suggest that a wide range of models for the thermal evolution of Mercury's interior may be consistent with the idea that early despinning of the planet with concurrent global contraction could be responsible for a N-S preference in lobate scarp orientation. That the amount of radial contraction in the first 0.5 Gyr is strongly sensitive to initial temperatures of the interior is not entirely surprising, because hotter interiors will have lower viscosities and thus more vigorous convection, and can cool quickly toward quasi-equilibrium with heat output. Interestingly, these results also include those simulations that are the closest to being consistent with the post-4.0 Ga accumulation of strain as well [2]. This observation, however, raises an intriguing question: why is it relatively simple to generate thermal history models that satisfy the strain constraints provided by despinning in the first 0.5 Gyr of Mercury's history, but finding reasonable models that match the post-4.0 Ga constraint requires either extraordinary compositions or considerably more strain than is recorded in the lobate scarps imaged by Mariner 10? Indeed the results found here may buttress the idea that additional contractional strain is recorded in the lithosphere by means other than in lobate scarps, like long-wavelength folds [8] or pervasive, small-scale faulting not resolved by Mariner 10 [1].

Clearly, data obtained by the MESSENGER mission to Mercury will greatly influence this analysis. Of paramount importance is a more robust determination of the somewhat contentious notion [3, 4] that there is, in fact, a preferred orientation to the lobate scarps. Additionally, global MDIS imagery better optimized for morphometric analysis and topographic data (from MDIS stereo images and MLA ranges) can be used to estimate better the amount of strain recorded in the lobate scarps, as well as potentially identify hidden strain on Mercury.

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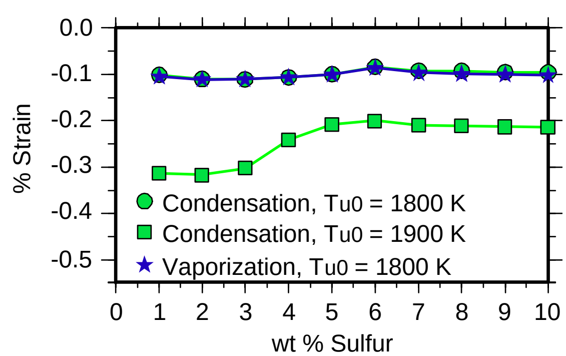

Figure 1. Pre-LHB contractional strain as a function of bulk core sulfur content, heat production composition, and initial mantle temperature.