DEPTH OF FAULTING IN MERCURY'S NORTHERN HEMISPHERE FROM THRUST FAULT MORPHOLOGY.
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Introduction Thrust faults, the most widespread tectonic feature observed across Mercury, are thought to reflect substantial crustal shortening resulting from interior cooling [1]. The orientations of thrust structures show no clear evidence of a globally coherent lithospheric fracture pattern, consistent with a homogeneous stress field principally induced by a contracting planet [1]. The surface deformations associated with these thrust faults are generally referred to as "lobate scarps"; these landforms exhibit a steeply sloping forelimb and and gently sloping back limb in cross section [1,2]. The surface morphology of lobate scarps is consistent with thrust-fault-related folds observed on Earth [2](**Fig. 1a**).

Previous photogeological studies [1] and thermal models [9] indicate that Mercury has shrunk in radius by as much as 5–7 km in diameter since ~ 4 Gyr ago. In this study, we modeled several thrust fault-related folds to characterize the geometry of the underlying faults, and to understand how shortening strain is partitioned within Mercury's intercrater plains and the northern smooth plains units. Additionally, assuming the maximum depth of faulting (Z_{BDT}) is the depth to the minimum brittle–ductile transition [11], thermal gradients at time of fault formation can be calculated.

Fault Identification and Geological Units: Faults suitable for modeling were identified using mapped structures [1] and selecting those with clear topographic signatures in the northern hemisphere, where laser-altimetry derived topography is available. Faults were identified in each of the two major geological units that dominate the north polar region [8]. In the planet's north, the "northern smooth plains" (NSP) is volcanic in nature and occupies 7% of Mercury's surface [7]; it is associated with low topography and thin crust [5] (**Fig. 3**). The older "intercrater plains" (ICP) represent the most extensive geological unit on the planet [7].

Fault Modeling: The boundary element dislocation program Coulomb was used to model the surface displacements of the faults [6]. Topographic profiles extracted perpendicular to fault strike were averaged to determine representative profiles. The standard deviation among profiles was computed, and the mean value was then used to quantify the misfit level for acceptable models (**Fig. 1b**).

A thrust-fault-related fold is an anticline that forms above the buried tip of a thrust fault[1,2]. The burial depth (Z_U), dip angle (θ), and the maximum depth (Z_{BDT}) of a given fault were iteratively adjusted to determine the lowest root mean square error (RMSE) between a given model and its topographic profile. The initial magnitude of surface displacement was held constant and estimated from the height of the scarp since, in the absence of erosion, we assumed that the relief of a given landform corresponds to the throw of the underlying fault [2].

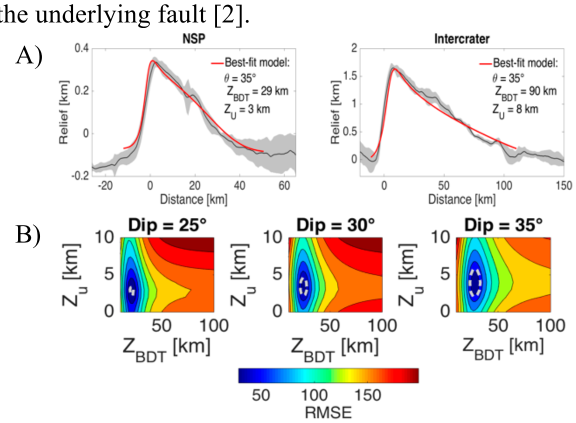

Figure 1: A) Example of best-fit models (red) for NSP and ICP faults. The solid black line shows the averaged topographic profile. The shaded grey region is ±one standard deviation of the stacked profiles B) Root-mean-square error (RMSE) contoured against Z_{BDT} and Z_U for the NSP faults using θ = 25°, 30 °, and 35°. The white dashed contour denotes the mean standard deviation among the profiles. The lowest RMSE is used as the best-fit profile.

Fault Morphology: Twenty faults were modelled in total: 17 faults in the NSP and three in the ICP.
Relief. All 17 NSP faults show a remarkably uniform relief of ~400 ± 140 m, whereas fold relief within the ICP of 1–2 km is considerably higher and more variable. The relief difference between NSP and ICP can be seen in **Fig. 1**.
Depth of faulting. Our modeling indicates that in the NSP, Z_{BDT} ranges from 11 to 40 km with an average of 25 km. Faults located in the western edge of the NSP region consistently penetrate to a depth of 20 to 40 km, whereas faults in the eastern part of the NSP are shallower, ranging in depth from 11 to 20 km. The depth of faulting (Z_{BDT}) is compared with a contour map of crustal thickness (Z_c) in **Fig. 2**. Thrust faults in the west penetrate nearly or entirely through the crust and into the mantle. The Z_{BDT}/Z_c ratio for each fault in the western portion of the NSP is on average 1.1±0.2,

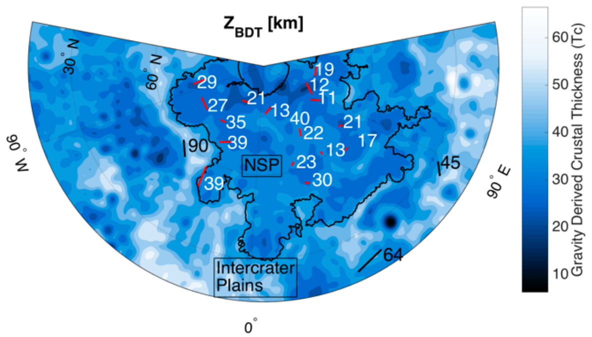

Figure 2: Stereo projection showing the Z_{BDT} for all 20 faults modelled. The location of the NSP is outlined in black. The red lines plot the length and location of faults in the NSP. The ICP faults are outlined in black. The contour map is crustal thickness (Z_c) estimates derived from Bouguer anomalies [5].

whereas those in the eastern portion, which penetrate to shallower depths, have a mean Z_{BDT}/Z_c ratio of 0.61±0.3.

Z_{BDT} estimates in the ICP are substantially higher, ranging from 45 to 90 km. All ICP faults penetrate into the mantle, with Z_{BDT}/T_c ratios of 1.25 – 2.

Discussion: Based on depth/diameter ratios of buried craters, the NSP is thought to have been resurfaced by 1 – 3 km of basalt [3]. Thrust faults on Mars [11] have been suggested to be confined to the uppermost volcanic deposits, as layered volcanic strata promote faulting that exploits mechanical detachments within the flow units. Given the similar geological setting, faulting within the NSP has been suggested to be restricted the volcanic cover [1]. Under this interpretation, thrust faults in the NSP have not likely accommodated much shortening strain from global contraction [1]. However, our modelling results indicate that these faults, in fact penetrate far into the lithosphere, and thus would accommodate a considerable amount of shortening strain from global contraction.

Additionally, there is a disproportionately large number of contractional landforms in the NSP: about 28% of total faults mapped on Mercury occur in about 7% of the surface area [1]. Under a scenario where a global contraction-induced horizontally isotropic stress field arose on Mercury, the greater number of faults in the NSP could explain the discrepancy in relief between the two units. If the lithosphere of the NSP is mechanically weaker, possibly by layered strata, this would permit the formation of many small landforms [1,11]. In contrast, shortening strains would concentrate into fewer, larger structures in a mechanically stronger ICP unit [1,11].

Large spatial variations in Z_c could serve to localize strain and would promote faults that accumulate a considerable amount of along-slip displacement, and thus relief, from global contraction [1]. In the ICP, Z_c varies between 60–10 km (**Fig 2**); in contrast, the relatively uniform Z_c values in the NSP would facilitate a more homoegeneous distribution of stress.

Comparing the cumulative relief of faults within equal areas between the NSP and ICP would provide an additional test of these findings. If the relief is equal, it would suggest that shortening strain from global contraction was spatially homogenous.

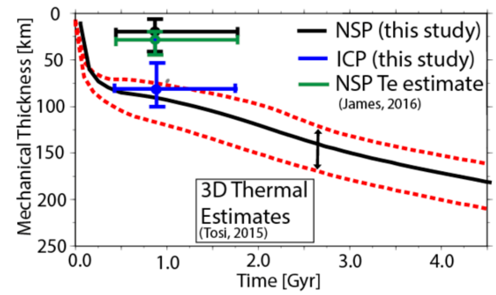

Figure 3: The range in mechanical thickness (Z_m) derived from a 3D thermal evolution model. Black and blue are estimates from this study. Green is an elastic thickness estimate from gravity admittance data [4].

Mechanical Thickness Estimates: Assuming that faulting penetrates to the brittle–ductile transition (BDT), mechanical thickness (Z_m) estimates can be derived from Z_{BDT} as given by the relation [9]:

$$Z_m = \frac{(T_m - T_s)Z_{BDT}}{T_{BDT} - T_s} \quad (1)$$

The surface temperature T_S was calculated for each fault using the daily thermal average at 1m depth, estimated from Mercury's 3:2 spin–orbit resonance [8]. The temperature at the BDT (i.e., T_{BDT}) was determined assuming a dislocation creep regime and equating the brittle and ductile strength of Mercury's lithosphere at Z_{BDT} [9].

Estimates of Z_m from a 3D thermal evolution model [9] were compared with Z_m values from this study (black and blue), as well as an elastic thickness estimate [4] for the NSP derived by gravity admittance (green).The average Z_m value of 80 km for the ICP is consistent with the thermal model predictions. Both this study and gravity admittance, suggest that Z_m is much less than that predicted by the thermal evolution model, consistent with higher temperatures associated with emplacement of the NSP.

References: [1] Byrne et al. (2014) *Nature Geosci*., 7, 301-307 [2] Byrne, P. K. *et al*. (2016) LPS 47, abstract #1022.[3] Head et al., *Science*, 333, 1853-1856 [4] James et al. (2016) *LPS XLVII,* Abstract #1992 [5]Mazarico et al. (2014) J.Geophys 119, 2417-2436 [6] Okada Y. (1992) *Bull. Seismol. Soc. Am*. 82, 1018 – 1040 [7] Procker et al. (2016) *LPS XLVII,* Abstract #1245 [8] Siegler et al. (2013) *Geohpys. Res. Planets* 118, 930 – 327 [9] Tosi et al. (2015) *Geophys. Res. Lett*., 42, 7327-7335 [10] Watters T.R (2002) *Geophys. Re. Lett.,* 29, 1542[11] Watters T.R (2004) *Icarus* 171, 284-294