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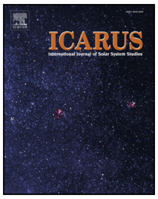

Tectonic patterns of shortening landforms in Mercury's northern smooth plains

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ABSTRACT

Mercury's northern smooth plains are volcanically emplaced units characterized by ghost craters, volcanically buried impact basins, and thrust fault-related landforms. We analyzed the thrust fault-related landforms, traditionally categorized as lobate scarps and wrinkle ridges, within the northern plains in order to describe trends in how these landforms are organized and oriented and what style of deformation (either thin or thick-skinned) their map patterns represent. Our analysis also establishes geologic constraints for which global processes may have produced stresses contributing to these tectonic patterns. We mapped 4853 thrust fault-related landforms in the northern plains at a map scale of 1:1,000,000 using three MErcury Surface, Space, ENvironment, GEochemistry, and Ranging (MESSENGER) global monochrome mosaics. These landforms, described as curvilinear asymmetric ridges, frequently occur in complex geometrical arrangements that are interpreted to share similar structural characteristics. We called these arrangements “compound landforms”. Like prior studies, we observed thrust faults to follow rims of buried craters. We also observed (1) sigmoidal rises bounded by fault-related landforms, (2) V-shaped rises composed of two landforms terminating at a single sharp point, (3) broad arcuate rises of nearly equal width, (4) parallel, evenly-spaced ridges, and (5) landforms showing alternation in direction of tectonic transport along strike. Respectively, we interpreted these landforms as transpressional uplifts, faults with sharply juxtaposing ramps, pop-up structures, fold and thrust belts, and antithetic fault intersections. By comparison with Earth analogues and patterns produced in numerical and physical models, our results suggest that deformation in the NSPs is thin-skinned. Orientation analysis showed that the northernmost landforms (90°–70°N) were predominantly oriented east–west while most of the landforms between 50° and 30°N were oriented north–south. Variations in orientation with latitude indicate that the growth of thrust fault-related landforms was influenced by sources of stress other than global contraction. If reorientation of the pole due to the formation of the Caloris basin impact did occur, the pattern of fault orientations indicates that geologic processes producing the pattern operated after reorientation.

1. Introduction

1.1. *Overview of the tectonics of the northern smooth plains*

Mercury's Northern Smooth Plains (herein referred to as the northern plains) is an expanse of smooth terrain volcanically emplaced (Head et al., 2011) through multiple phases of resurfacing events (Ostrach et al., 2015). The northern plains show very few superposing impact craters (Ostrach et al., 2015) and small, isolated regions of rough topography (Susorney et al., 2017). These plains embay heavily cratered terrain producing gradational to sharp physiographic boundaries (Denevi et al., 2013). The northern plains are abundant with ghost craters, volcanically flooded craters recognized by rings of tectonic origin showing high topography likely localized above buried crater rims with lower topography interior to these rings, and volcanically flooded impact basins with rims jutting above the volcanic units (e.g. Freed et al., 2012; Klimczak et al., 2012; Watters et al., 2012). This suggests that heavily cratered terrain once extended up to the north pole, and then was buried by widespread effusive volcanism between ~3.7 and 3.9 Ga (Head et al., 2011; Denevi et al., 2013; Ostrach et al., 2015). As evidenced by the sharp contrast in the frequency of superposing craters between the northern plains and heavily cratered terrain, the northern plains are inferred to be younger than their underlying units. Regionally, the northern plains units are estimated to be ~1–2 km thick (Ostrach et al., 2015). The topography of the northern plains is 2 km below the global average elevation and shows lower

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slopes than surrounding terrains (Zuber et al., 2012). This region also contains a ~950 km diameter topographic rise, commonly referred to as "the northern rise", that stands ~1.5 km above the surrounding terrain (Zuber et al., 2012).

In addition to fresh and buried impact craters, thrust fault-related landforms are also prevalent in the northern plains (Byrne et al., 2014). These thrust fault-related landforms have traditionally been categorized into three groups based on morphology (Strom et al., 1975; Dzurisin, 1978; Watters, 1988; Watters et al., 2004, 2009 and many others): wrinkle ridges, lobate scarps, and high relief ridges. Wrinkle ridges have often been observed as anastomosing, arcuate, asymmetric ridges. They are interpreted to be anticlines above blind thrust faults, but for many of these landforms, a surface breaking fault is visible (Watters, 1988; Golombek et al., 1991; Schultz, 2000; Walsh et al., 2013; Watters et al., 2015a). They are more commonly observed in younger volcanic plains than heavily cratered terrains on Mercury and other bodies (Strom et al., 1975; Watters, 1988; Golombek et al., 2001) and are distinguished from the other common thrust fault-related landforms on Mercury, lobate scarps and high relief ridges, by their complicated, sinuous morphology. In contrast, lobate scarps are linear to arcuate asymmetric ridges with a fault trace intersecting the surface immediately in front of the steeper slope. High relief ridges are symmetric in cross section and rare compared to the previously discussed landforms. They are interpreted to be anticlines overlying high-angle reverse faults.

Although their individual morphologies (e.g. Watters, 1993) have been qualitatively described, wrinkle ridges, lobate scarps, and high relief ridges are not discrete, clearly distinguishable landform types. End member-type landforms that fit previous descriptions do exist as exemplars within each category, but we observe the vast majority of thrust fault-related landforms within the northern plains to exist on a spectrum between these three groups. Furthermore, classification of landforms as wrinkle ridges or lobate scarps does not facilitate the mapping process or our understanding of how the underlying structures form and link. Thus, we do not attend to the traditional terminology, similar to the approach taken by Byrne et al. (2014), and do not categorize our mapped thrust fault-related landforms in the traditional sense. Rather, we map fault surface breaks and anticline crests and identify isolated landforms, referred to as thrust fault-related landforms and larger, more complex landforms, referred to as compound landforms from hereon. Compound landforms consist of geometrically related anticlines and traces that, by comparison with analogues, are interpreted to share a structural relationship. In using a single term to describe the landforms, most of these landforms would have been classified as wrinkle ridges, and the detail of their structure would have been lost.

Thrust fault-related landforms in the northern plains on Mercury have not previously been mapped in sufficient detail to describe map patterns and regional trends in landform morphology and orientation. Detailed morphological descriptions, identification of map patterns, and structural interpretations of these landforms can constrain their subsurface fault architecture, thickness and geometry of the plains deposits, and details of the global or regional processes associated with their formation.

In particular, observational and statistical analyses of morphologies and map patterns and comparison of landform characteristics with planetary analogues could suggest whether faults below northern plains structures are confined within the volcanic plains units or whether they root deeper into the subsurface. Based on results from elastic dislocation modeling and comparison with Earth analogues, Watters (2004) proposed that thrust faults in the Martian plains shallowly root into upper volcanic units. Other studies have also suggested that ridges on Mars are underlain by faults that penetrate primarily upper units and regolith, evidenced by modeling, landform geometry, and again, the resemblance of these structures to terrestrial landforms (e.g. Plescia and Golombek, 1986; Watters, 1988; Mangold et al., 1998). Comparisons to terrestrial landforms indicate that structural styles in these terrains are similar to thin-skinned tectonics on Earth. For example, the Yakima fold and thrust belt in the Columbia Plateau of eastern Washington has been suggested as an analogue to thrust fault-related landforms in flood basaltic units on Mercury, the Moon, and Mars due to their basaltic composition, systems of parallel ridges, and low-lying, only slightly deformed regions between those ridges (Plescia and Golombek, 1986; Watters et al., 2004). The faults underlying this thrust belt shallow into a décollement less than 10 km below the surface (Casale and Pratt, 2015).

In contrast, Peterson et al. (2017) contend that northern plains thrust faults extend deeper into regolith and cratered units underlying the plains because elastic dislocation modeling results best produced observed topography when model faults are deep-seated. Similar conclusions have been drawn by Schultz (2000), Golombek et al. (2001), and Montési and Zuber (2003) for thrust fault-related landforms on Mars based on kinematic model results best resolved by faults that do not shallow into décollements and spatial and topographical relationships between parallel landforms which could result from deeply rooted faults. A similar deformation style to that suggested has been observed on Earth in the Rocky Mountains of Wyoming, and is called thick-skinned tectonism, in which thrust faults extend down to a crystalline basement (e.g. Pfiffner, 2017). Landforms like the Wind River thrust fault share similar topography and length relationships to thrust fault-related landforms on Mercury (Watters and Robinson, 1999), and thus can be suggested as analogues to northern plains thrust fault-related landforms. Contrasting analogues and a lack of detailed mapping have limited consensus for the depth of faulting underlying the northern plains structures.

1.2. Tectonic processes and associated stress states on Mercury

The tectonics of Mercury have been influenced by many global and regional processes, including impact cratering, tidal despinning, cooling, subsidence, and changes in orbital parameters that lead to differential surface temperature conditions and changes in solar tides. Each of these processes induces a unique set of stresses within the lithosphere. Impact shock waves propagate from the location of impact and excavate rock, producing the negative topography associated with impact craters (Melosh, 1989). For the remainder of these processes, the orientations and magnitudes of the principal stresses control whether the lithosphere experiences permanent strain and, if so, whether it is accommodated by shortening or extension. To produce faults, principal stresses must be compressive in all orientations (vertical and horizontal) and be of sufficient difference to one another to overcome the strength properties of the host rock. The orientation of the intermediate principal stress determines the 3D geometry of those faults (Anderson, 1951; Jaeger et al., 2007). Once a fault has formed, it may continue to grow or new similarly oriented faults may propagate until the directions of stresses change or until stresses are no longer sufficiently large to promote failure.

Impact cratering and global cooling are the geologic processes that likely operate over the longest time-scales on Mercury. During the first ~0.5 Ga of solar system history, impacts were more frequent and destructive due to a more substantial population of impactors and a higher concentration of larger-bodied impactors within that population (Marchi et al., 2013). These impacts drove the formation of impact craters and basins, which have degraded over time (e.g. Fassett, 2012; Kinczyk et al., 2016). Global cooling would have prompted global contraction, that is found to have lead to widespread thrust faulting with increased activity early in Mercury's history that slowed down substantially by ~3 Ga (Banks et al., 2015; Crane and Klimczak, 2017). Stresses from global contraction are estimated to be horizontally isotropic, and therefore, if large enough, these stresses should have formed a planet-wide distribution of randomly oriented thrust fault-related landforms (Solomon, 1976, 1978; Watters et al., 2001, 2004).