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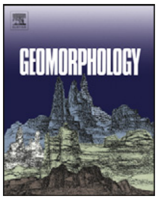

Channel slope reversal near the Martian dichotomy boundary: Testing tectonic hypotheses

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ABSTRACT

Faults along the Martian dichotomy boundary are evidence of tectonic activity, which by analogy with terrestrial tectonism may cause changes in or even reversal of fluvial longitudinal profiles. In the eastern hemisphere between 30° E and 150° E, this tectonic activity has been hypothesized to result from lower crustal flow or from lithospheric flexure, for which loading (e.g., by material deposition) of the northern lowlands is a possible cause (Watters, 2003a; Nimmo, 2005). The topographic (slope) changes resulting from these two different mechanisms are distinct and can provide a means for distinguishing between them, although other processes may complicate interpretations of reversed longitudinal profiles. Two fan-shaped networks of inverted channels are located near 150° E in the Aeolis Dorsa region just north of the dichotomy boundary. Their original flow directions, inferred from planform morphology, suggest flow to the northeast in contrast to their current longitudinal profiles sloping down to the southwest. This contrast indicates slope reversal. We investigate the lower crustal flow and flexure mechanisms for slope reversal by testing three different hypotheses: 1) lower crustal flow, 2) flexure caused by material erosion from the highlands and deposition in the lowlands, and 3) flexure caused by highland erosion and deposition in the lowlands plus deposition of the Medusae Fossae Formation in the lowlands. We test these three hypotheses by comparing the inferred magnitudes of the slope reversals with predicted slope changes from geophysical models for these processes. Taking the possibility of non-tectonic (i.e., collapse) processes into account, our results suggest that, among these three models, the slope reversal is most consistent with the predicted tectonic response to erosion and deposition of highland material in conjunction with deposition of the Medusae Fossae Formation. Contrary to previous findings, our results do not support the mechanism of lateral crustal flow, although they do not rule it out because lower crustal flow and erosion may both have been operating, but on different time scales. The result of this hypothesis-testing provides insight into the evolution of the dichotomy boundary and Martian crust in this location.

1. Introduction

One the most prominent features of the geology of Mars is the dichotomy boundary, the global topographic and geologic contact separating the older and heavily cratered southern highlands from the more recent and relatively smoother northern lowlands. The boundary is a narrow region that occupies an ~700 km wide belt around the planet and is characterized by a distinct change in elevation, with the highlands standing 2 to 5 km above the lowlands (e.g., Watters et al., 2007). The dichotomy boundary is expressed both as a distinctive topographic change and as a change in crustal thickness, with an average crustal thickness of 32 km in the northern lowlands, 58 km in the southern highlands (e.g., Zuber et al., 2000; Watters et al., 2007), and 55 ± 20 km near the dichotomy (Nimmo, 2002; Wieczorek and Zuber, 2004). The crustal dichotomy boundary is spatially correlated with the topographic dichotomy boundary only between 110° and 190° E (e.g., Zuber et al., 2000).

The dichotomy boundary is a complex and enigmatic structure. Hypothesized to have formed early in the history of Mars (e.g., Watters, 2003a; Frey, 2004; Watters et al., 2007; Andrews-Hanna et al., 2008), it has been modified by tectonic, mass wasting, fluvial, aeolian and glacial processes (McGill and Dimitriou, 1990; Watters and Robinson, 1999; Watters, 2003a,b; Irwin et al., 2005; Tanaka et al., 2005), whose timing is poorly constrained. Between 30° E and 150° E in the vicinity of the dichotomy boundary, the presence of large-scale faults is evidence of tectonic deformation (Guest and Smrekar, 2005). On Mars, large-scale processes that may generate tectonic stresses include lower crustal flow. This horizontal flow, which occurs in a ductile lower crust, is generated by lateral pressure gradients caused by differences in crustal thickness, and over time leads to reduction in crustal thickness variations (e.g., Zuber et al., 2000; Nimmo and Stevenson,

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2001; Nimmo, 2005). Alternatively, large-scale tectonic stresses may be generated by lithospheric flexure that occurs in response to erosion and redeposition of surficial material (e.g., Tanaka et al., 2001; Searls and Philips, 2004; Nimmo, 2005). On Mars, lower crustal flow and lithospheric flexure are hypothesized to have contributed to modifying the dichotomy boundary (Watters, 2003a; Nimmo, 2005).

Comparing these mechanisms with observations of tectonic deformation may help constrain the evolution of the dichotomy boundary (Nimmo, 2005) and the conditions of early Mars. For instance, reduction of variation in local or regional crustal thickness caused by lower crustal flow is temperature-dependent and provides, therefore, a constraint on the thermal evolution of the crust (e.g., Parmentier and Zuber, 2007). If lower crustal flow occurred, then it places constraints on the thermal state of the crust at that time, which has implications for our understanding of the internal evolution of Mars. Likewise, determination of the elastic thickness of the lithosphere also constrains the thermal gradient, because the depth of the lower limit at which ductile response replaces brittle response is essentially governed by temperature (e.g., Solomon and Head, 1990). Determination of the elastic thickness is, therefore, important to reconstruct the thermal history of Mars.

Lower crustal flow and lithospheric flexure may cause significant surface deformations, as observed on Earth where, for example, lower-crustal flow contributes to the evolution of the Tibetan plateau (e.g., Royden et al., 1997; Bendick and Flesch, 2007), material deposition in sedimentary basins is a cause of lithospheric flexure (e.g., Watts et al., 1982; Watts, 1989), and flexural isostasy of the lithosphere has contributed to the drainage reversal of the Amazon river (Sacek, 2014). On Mars, each of these mechanisms (lower crustal flow and flexure caused by erosion/deposition) would produce different topographic modifications, namely, different amounts or directions of land surface tilting. Thus, a test for the cause of the tectonic deformation is the amount or direction of change or even reversal of local or regional slopes. Slope change or reversal may be inferred through discernment that the current slopes of features do not match the original slopes, such as the tilting of impact craters with originally horizontal floors (e.g., Irwin and Watters, 2010) or modification of longitudinal profiles of fluvial forms. Analysis of the longitudinal profiles of fluvial channels is a technique that has been widely used on Earth to identify and characterize tectonic deformations (e.g., Seeber and Gornitz, 1983; Demoulin, 1998; Holbrook and Schunun, 1999; Snyder et al., 2000; Jain and Sinha, 2005; Chen et al., 2006; Larue, 2008; Lahiri and Sinha, 2012; Roberts et al., 2012). The availability of high-resolution Martian geomorphic and topographic data allows us to apply the same technique to Mars.

Close to the dichotomy boundary north of Terra Cimmeria, inverted (positive-relief) fluvial features are observed in the Aeolis Dorsa region (formerly referred to as the Aeolis–Zephyria Plana) in the western Medusae Fossae Formation (MFF) (e.g., Pain et al., 2007; Burr et al., 2009, 2010; Zimbelman and Griffin, 2010). Previous analysis has shown that instead of sloping monotonically downward, the longitudinal profiles of some of these features undulate, indicating some post-flow modification (Lefort et al., 2012). Such modification may have been caused by multiple and possibly concurrent processes, such as sediment compaction or collapse and tectonic deformation. In addition, the original flow direction and channel slope for many of these fluvial features are not conclusively known, making slope or direction changes difficult to determine. Where sedimentary causes may be ruled out and the original flow conditions inferred from the geomorphology, however, changes in slope can be inferred.

Of the multiple branching networks of inverted fluvial features in the Aeolis Dorsa, two networks have large-scale, fan-shaped plan view morphologies. These morphologies provide constraints on the original flow direction, and allow the original slopes to be estimated from comparison to other similar fan-shaped networks on Earth and Mars. Undulations in the longitudinal profiles of some of these features suggest that modification by sedimentary processes (e.g., compaction, collapse) may have occurred, but these undulations are small (<100 m amplitude, ~<15 km in wavelength; Lefort et al., 2012) compared to the scale of the fluvial networks. Thus, these fluvial features with regional-scale slopes that are reversed from the estimated original slopes may be used to differentiate between the possible mechanisms for tectonic deformation. Tectonic activity in this location is implied by the presence of an inferred extensional fault along the southwestern boundary of the western MFF (McGill and Dimitriou, 1990; McGill et al., 2004) in the Aeolis Dorsa region (Fig. 1).

In this work, we use multiple datasets to derive the current slopes along the best-preserved and coeval individual fluvial features in these two fan-shaped networks. Based on morphological analysis and comparison to slopes found in morphologically similar terrestrial and Martian branching networks, we infer the magnitude of the slope reversals. We then compare these magnitudes to model slope changes for each tectonic deformation mechanism to test among three proposed deformation scenarios: 1) a lower-crustal flow model, 2) a lithospheric flexure model caused by material erosion from the highlands and deposition in the lowlands, and 3) a lithospheric flexure model including highlands erosion and deposition in the lowlands as well as MFF deposition in the lowlands. Our results are complicated by the possibility of local deformation caused by collapse in the south, between these networks and the dichotomy boundary. Geospatial relationships, however, suggest that only one of the two networks may have been affected by collapse and that this process most likely did not have a significant influence on the slope reversal. For both networks, the results are conclusively more consistent with the erosion–deposition model including deposition of the MFF than with the lower crustal flow model. From those results, we derive implications for the type and timing of the crustal processes that occurred at this location along the Martian dichotomy boundary.

2. Regional background: the Medusae Fossae Formation and the Aeolis dorsa

The MFF is an extensive, light-toned, friable, layered deposit likely composed of volcanic ash deposits (e.g., Scott and Tanaka, 1982, 1986; Bradley et al., 2002; Hynek et al., 2003; Mandt et al., 2008) and up to 3.5 km thick in places (Scott and Tanaka, 1986; Greeley and Guest, 1987; Hynek et al., 2003; Watters et al., 2007). It is situated along the dichotomy boundary between 130° and 240° E. Its present extent is estimated to be 2.1–2.5 × 10^6 km^2 and its present volume to 1–1.9 × 10^6 km^3, although it may have once covered up to 5.7 × 10^6 km^2 (Bradley et al., 2002; Harrison et al., 2010). Although the MFF was previously dated to the Amazonian epoch (e.g., Scott and Tanaka, 1986; Tanaka, 1986; Head and Kreslavsky, 2001, 2004; Werner, 2006), recent work suggests that it was largely in place by the (late) Hesperian (Burr et al., 2009; Kerber and Head, 2010; Zimbelman and Scheidt, 2012).

The western MFF corresponds to the lowest and, therefore, oldest member of the MFF, and contains the Aeolis Dorsa, an extensive and numerous population of sinuous ridges. These ridges have been interpreted as inverted fluvial paleochannels or meander belts (Burr et al., 2009; Zimbelman and Griffin, 2010), formed by surface runoff, chemical cementation of the fluvial sediments, burial by subsequent deposition, and finally exhumation and inversion by aeolian abrasion (Pain et al., 2007; Burr et al., 2009, 2010). Whereas another positive-relief flow network has been noted in the central part of the MFF (Harrison et al., 2013), the Aeolis Dorsa contains the highest density of inverted surface flow features identified in these deposits (Burr et al., 2009).

The two large fan-shaped networks of paleochannels that are the focus of this study are located ~275 km north of the dichotomy boundary (Fig. 1). These networks display a complex stratigraphy, as shown by relative elevations, overlapping relationships and surface textures. For example, in Fig. 2, the surface of the fan-shaped plateau, marked