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Thrust fault vergence directions on Mars: A foundation for investigating global-scale Tharsis-driven tectonics

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[1] Insight into the mechanical and thermal structure of the Martian lithosphere and the character of Tharsis-driven tectonics is gained from detailed mapping of the global distribution of thrust fault vergence directions with respect to the center of the Tharsis tectono-volcanic province. Our results reveal sub-equal frequencies of thrust faults that verge away from and toward Tharsis. Based on the observed distribution of thrust fault vergence directions, we conclude that the base of the Tharsis load was effectively welded, by frictional and cohesive strength, to the subjacent Noachian crust throughout its periods of sustained volcanism and faulting during the late Noachian to early Hesperian, rather than being detached along a ductile layer at its base. *INDEX TERMS:* 8010 Structural Geology: Fractures and faults; 8005 Structural Geology: Folds and folding; 8015 Structural Geology: Local crustal structure; 8149 Tectonophysics: Planetary tectonics (5475). **Citation:** Okubo, C. H., and R. A. Schultz, Thrust fault vergence directions on Mars: A foundation for investigating global-scale Tharsis-driven tectonics, *Geophys. Res. Lett.*, *30*(22), 2154, doi:10.1029/2003GL018664, 2003.

1. Introduction

[2] The Tharsis tectono-volcanic province forms a hemisphere-scale topographic rise that extends up to 27 km above Mars' datum and was a focus of large-scale volcanism and faulting (Figure 1). Current geophysical models of the mechanical structure of Tharsis can be delineated by the proposed mechanical character of the base of the Tharsis volcanic pile, at its interface with the older Noachian crust. Based on observations of Tharsis-radial graben, a 'detached cap' model (Figure 2a) has been proposed. This model suggests that much of the base of the Tharsis volcanic pile is ductile and overlies a brittle Noachian crust [e.g., *Banerdt and Golombek*, 1990; *Tanaka et al.*, 1991]. In this case, basal ductility is maintained by high heat flow due to magmatic activity localized at Tharsis. The base of Tharsis would exhibit brittle behavior only along its cooler periphery, where it is effectively welded to the brittle Noachian crust. Alternatively, the 'welded base' class of Tharsis models (Figure 2b) suggests that the entire base of the volcanic pile is brittle and welded to the subjacent brittle Noachian crust [e.g., *Solomon and Head*, 1982; *Phillips et al.*, 2001].

[3] In this paper, we compare predicted spatial patterns of thrust fault vergence directions implied by the detached cap and welded base models against vergence directions derived from Mars Orbiter Laser Altimeter (MOLA) topography for a global distribution of thrust-fault related folds. Within a deforming plate or wedge, the distribution of thrust fault vergence directions is sensitive to the shear strength of the subjacent basal material, for those thrusts that have down-dip lengths comparable to the brittle thickness the plate [*Davis and Engelder*, 1985; *Montési and Zuber*, 2003]. Where a section of brittlely deforming plate or wedge overlies a mechanical ductile layer (e.g., a salt or magma layer), thrust faults that verge away from the source of the causative driving stress (outward-verging) are predicted to occur in sub-equal frequencies to thrust faults that verge toward the driving stress source (inward-verging). Conversely where basal shear strength is higher (but less than the shear strength of the surrounding crust), a consistent outward thrust fault vergence is predicted, in characteristic style of accretionary wedges. Recent developments in planetary tectonics have made the determination of thrust fault vergence directions from topography possible, and thrust fault-related folds on Mars have been shown to cut through the crust down to the brittle-ductile transition [*Montési and Zuber*, 2003]. Thus the frequency of thrust fault vergence directions on and around Tharsis can be used to infer the strength of its base and evaluate detached cap versus welded base geophysical models.

2. Procedure

[4] Planetary landforms termed 'lobate scarps' and 'wrinkle ridges' are commonly inferred to be surface expressions of thrust fault-related folds (Figure 3) [*Schultz*, 2000; *Schultz and Watters*, 2001; *Montési and Zuber*, 2003]. In topographic cross section, lobate scarps are characterized by a low asymmetric rise typically 100s of meters high and 10s of kilometers wide. By comparison, wrinkle ridges contain the low asymmetric rise of a lobate scarp, with additional narrow ridges on and along the rise that are typically 10s of meters high and a few kilometers wide. The low asymmetric rise of lobate scarps is interpreted to form in response to folding above a single primary surface breaking thrust fault [*Schultz and Watters*, 2001]. The low rise component of wrinkle ridges is generally considered to reflect folding above a primary blind thrust fault, while the characteristic narrow ridges are interpreted to form above smaller secondary forethrust or backthrust faults [*Schultz*, 2000]. Along-strike trace lengths of both lobate scarps and wrinkle ridges can extend for 100s of kilometers, with shorter highly arcuate examples occurring within and concentric about the center of impact craters and other structural basins.

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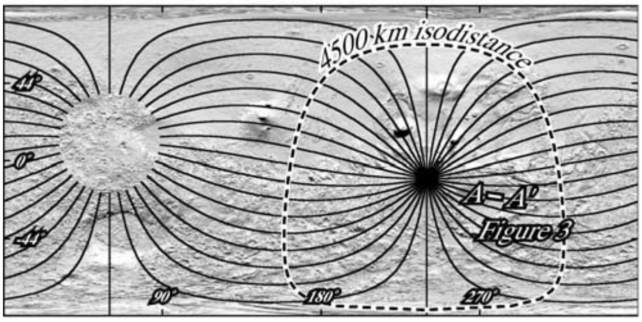

Figure 1. MOLA-based shaded relief map in cylindrical equidistant projection showing locations of the topographic profiles (solid lines) used in this study. Profiles radiate along great circles from an origin at 240°E, 10°S, on the Tharsis topographic high. The 4500 km isodistance from this origin is shown for scale (closed dashed line).

[5] Previous mapping efforts have revealed wrinkle ridge and lobate scarp traces that are generally concentric about Tharsis [*Watters and Maxwell*, 1983; *Chicarro et al.*, 1985; *Anderson et al.*, 2001]. We build upon these results and measure thrust fault vergence directions along Tharsis-radial profiles of MOLA topography using a slope asymmetry analysis method presented by *Okubo and Schultz* [2003]. Interpretation of vergence direction by this method relies upon field observations and mechanical and kinematic model predictions, which show that the limbs of thrust fault-related folds are consistently asymmetric in cross-strike profile. The subjacent thrust is shallowest below the steepest fold limb and dips toward and below the shallower sloping fold limb. Thus, the thrust verges from the shallowest sloping fold limb toward the steepest sloping fold limb, in the direction of hanging wall displacement above the thrust. We use this relation to interpret thrust fault vergence directions along thirty-six, 9000-km-long topographic profiles radial to the center of Tharsis, as defined by its thickest section of crust mapped by *Zuber* [2001] (Figure 1). Our topographic profiles are constructed along great circles separated by 10 degrees in azimuth. We use the MOLA Mission Experiment Gridded Data Record (MEGDR) version 2.0 [*Smith et al.*, 2003] digital elevation models (DEMs), at 128 pixels per degree (~0.455 km/pixel at the equator) resolution. The MEGDR's span the entire planet longitudinally between ±88° latitude in sixteen 90° by 44° grids. Although near polar areas are not covered by the MEGDR's, inspection of custom created MOLA-based DEMs [e.g., *Okubo et al.*, 2003] shows no visible thrust fault-related folds at the poles. The MEGDRs are sampled along each profile at 0.1 km intervals using the Generic Mapping Tools [*Wessel and Smith*, 1998] routine 'gridtrack'. To facilitate identification of thrust fault-related folds in profile, the location of each profile is plotted on MEGDR-based shaded relief maps. Vergence directions for each thrust fault-related fold identified in map view are then interpreted using slope asymmetry analysis of the concurrent topographic profile. Finally, these vergence directions are verified by extracting additional adjacent topographic profiles from the MEGDRs using the program 'gridview' (http://core2.gsfc. nasa.gov). Vergence directions are measured for each tran-sected primary and secondary thrust fault-related fold greater than 10 m in height, regardless of orientation.

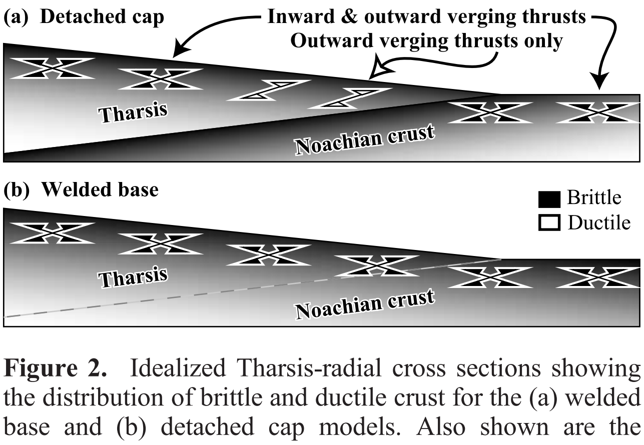

Figure 2. Idealized Tharsis-radial cross sections showing the distribution of brittle and ductile crust for the (a) welded base and (b) detached cap models. Also shown are the predicted thrust fault orientations for each model.

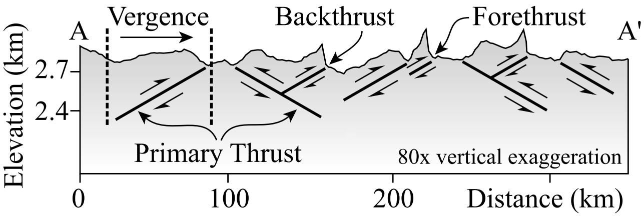

Figure 3. MEGDR-based Tharsis-radial topographic profile showing typical thrust fault-related folds in the Solis Planum region. See Figure 1 for location. General subjacent fault dip directions and offsets interpreted by the slope asymmetry method (see text) are shown in solid lines.

3. Results

[6] Our results show that in each topographic profile where more than one thrust fault-related fold is transected, the percentage of outward-verging thrusts is sub-equal to the percentage of inward-verging thrusts (Figure 4). Among the 9000-km set of profiles, the mean percentage of outward-verging primary thrusts is 48.8% with a standard deviation of 21.9, within a total of 559 measured thrusts. A spike in the frequency of outward-verging primary thrusts does occur in the 270° and 280° azimuth profiles (Figure 4a), corresponding to 5–15 more thrusts that verge relatively away from Tharsis along these profiles respectively. These thrusts are within and radial to Utopia Planitia, in the eastern hemisphere of Mars, and may be a result of local Elysium tectonics. These Utopia Planitia thrusts do not affect vergence frequencies closer to Tharsis (Figure 4b). Within 6000 km of the Tharsis center, the mean percentage of outward-verging primary thrusts is 47.5% (standard deviation of 28.3) for the 341 measured thrusts. On Tharsis proper, the mean percentage of outward-verging primary thrusts is 48.4% (standard deviation of 23.7) for those 246 thrusts within 4500 km of the Tharsis center. In all cases, the remainder of the measured thrusts verges toward Tharsis. Inclusion of secondary faults in these statistics results in negligible changes in these vergence frequencies since less than 10% of the mapped faults are identified as secondary thrusts, and these secondary thrusts also show sub-equal vergence frequencies.

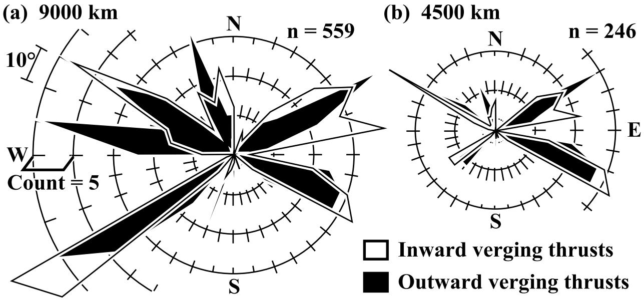

Figure 4. Rose diagrams showing vergence direction frequencies for primary thrust faults along (a) the entire 9000 km length of each profile and (b) a subset of thrusts within 4500 km of the profile origin. Vergence frequencies are generally sub-equal at both scales.

[7] Within some previously identified impact basins (e.g., Copernicus in Terra Sirenum), and other structural basins, thrust fault-related folds that are concentric about the basin center generally verge outward, rather than toward the basin center. Similarly, ring-shaped thrust fault-related folds (e.g., in Hesperia Planum), which are interpreted to outline buried impact craters [*Sharpton and Head*, 1988], also verge in an outward direction, away from the center of the postulated subjacent crater. Thrust fault-related folds that cross-cut basins and have trace lengths greater than the basin diameter generally do not show a preferred out-of-basin vergence, but rather verge in a direction consistent with sections of the fold outside of the basin, an observation in line with interpretations of thrust fault vergence based on geometric analysis of offset crater rims along thoroughgoing thrust fault-related folds [*Mangold et al.*, 1998]. Further, the basins that do exhibit predominantly out-of-basin thrust fault vergence directions are commonly less than 150 km in diameter. Within larger basins such as Solis Planum, a ~700-km-wide structural basin, thrust fault-related folds typically lack a predominant of out-of-basin vergence direction. In Solis Planum, previous studies have suggested a consistent outward vergence direction for these thrusts based on interpretations of elevation offsets across the related folds [*Golombek et al.*, 2001]. Interpretations of elevation offset alone, however, have been shown to produce conflicting vergence directions depending on the length of the topographic profile used [*Okubo and Schultz*, 2001]. The slope asymmetry analysis used here is not sensitive to profile length and thus provides consistent and reliable dip directions.

[8] Vergence directions obtained from slope asymmetry analysis of thrust faults within structural basins are included in the results of Figure 4. The overall effect of basin-related biases on our results is limited since the number of basin-influenced thrust-related folds (when present) is less than 10% of the total population in each profile, and the affected folds occur with sub-equal vergence direction frequencies relative to the center of Tharsis.

4. Discussion and Conclusions

[9] Our MOLA-derived thrust fault vergence distributions provide a test of the detached cap and welded base models since each of these models predicts a distinctive pattern of thrust fault vergence directions, which is dependent on the model-prescribed distribution of lithospheric rheology. The mechanical strength of the 'welded' contact between the brittle parts of the Tharsis base and Noachian crust exerts significant control on these model-predicted patterns of thrust fault vergence. The upper surface of the Noachian crust is primarily composed of impact-generated regolith [*Scott and Tanaka*, 1986], which analogous terrestrial deposits have shown to consist of highly angular clasts [e.g., *Grant and Schultz*, 1993; *Urrita-Fucugauchi et al.*, 1996]. Non-indurated materials composed of angular clasts can be as strong as pre-impact crustal rocks regardless of clast size and sorting [*Mair et al.*, 2002]. Therefore, relative to the strength of the intact Tharsis or Noachian crust, the Noachian regolith should not be considered as a mechanically weak layer or detachment. Thus the mechanical strength of the 'welded' contact can be regarded as comparable to the strength of the brittle parts of the Tharsis load and Noachian crust.

[10] The detached cap model predicts sub-equal distributions of thrust fault vergence directions above the ductile base of the Tharsis load (Figure 2a). This central area would then be ringed by an annulus of outward-verging thrusts near the edge of the Tharsis load, where basal shear strength increases toward the colder, brittle periphery, causing block rotations and asymmetric shearing [e.g., *Montési and Zuber*, 2003]. Here, basal shear strength is greater than along the central ductile base, but is less than the shear strength of the welded fully-brittle contact below the periphery of the Tharsis load. We would then predict sub-equal thrust fault vergence frequencies above the welded periphery of the Tharsis load and within the surrounding Noachian crust, with the subjacent lower crust acting as a ductile layer. This predicted 'bulls-eye' distribution of vergence directions, specifically the annulus of outward-verging thrusts, centered on Tharsis is not observed along our profiles. Further, the percentages of outward-verging thrust faults are comparable between the 9000 km, 6000 km and 4500 km profiles. Accordingly, the predicted pattern of thrust fault vergence directions associated with a detached cap model is inconsistent with our observations.

[11] In welded base models, the vertical distribution of mechanical strength within the Tharsis plus Noachian crust would generally increase with depth to the brittle-ductile transition. Most importantly, mechanically weak layers would not be present at the interface between the base of Tharsis and the top of the Noachian crust. Therefore in welded base models, thrust faulting occurs throughout the thickness of the Tharsis plus Noachian crust [e.g., *Montési and Zuber*, 2003]. Accordingly, welded base models are predicted to exhibit sub-equal thrust fault vergence frequencies everywhere at a regional scale due to faulting down to the brittle-ductile transition (Figure 2b). Consequently our observations of sub-equal thrust fault vergence direction frequencies (Figure 4) strongly support the welded base class of Tharsis models. Thus, at the time when the thrust fault-related folds were forming (e.g., late Noachian to early Hesperian), lateral spreading of Tharsis must have occurred independent of regional shearing along mid-crustal ductile horizons. If shearing did occur along a detached (ductile) Tharsis base, this process would have had to take place before the formation of the thrust-related

folds (and evidence of this event could be buried by subsequent volcanism).

[12] The detached base model was proposed in order to account for the widespread formation of narrow, closely-spaced Tharsis-radial graben swarms, which extend as far as 4500 km from center point of Tharsis used in this study [e.g., *Wise et al.*, 1979a, 1979b]. Stratigraphic mapping shows that these graben developed simultaneously on Tharsis and on its periphery concurrent with or younger than the development of the thrust fault-related folds [*Scott and Tanaka*, 1986; *Banerdt and Golombek*, 1990; *Tanaka et al.*, 1991]. Therefore, adoption of a welded base model necessitates styles of graben and thrust fault-related fold development that are independent of regional shearing along mid-crustal detachments, such as dike-induced graben formation [e.g., *Rubin and Pollard*, 1988; *Rubin*, 1992] and normal and thrust faulting down to the brittle-ductile transition [e.g., *Montési and Zuber*, 2003; *Wilkins and Schultz*, 2003]. A welded base model also eliminates the need for elevated heat flux along the base of the Tharsis load in order to maintain ductility. Thus, Tharsis graben and thrust fault-related folds may better reflect lithosphere-scale thick-skinned deformational processes, rather than thin-skinned deformation above a slipping mid-crustal detachment.

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