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Displacement-Length Relations of Thrust Faults Associated with Lobate Scarps on Mercury and Mars: Comparison with Terrestrial Faults

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Abstract. The displacement D and length L of thrust faults associated with lobate scarps on Mercury and Mars are estimated from topographic and planimetric measurements. D ranges from 0.29 to 3.58 km for mercurian thrust faults (n = 10) and from 0.27 km to 2.90 km for martian thrust faults (n = 13). The D-L relationship between thrust fault populations analyzed on Mercury and Mars is very similar ($\gamma_{Mercury} = 6.5 \pm 3.2\times10^{-3}$, $\gamma_{Mars} = 5.9 \pm 2.0\times10^{-3}$), and about an order of magnitude lower than terrestrial thrust faults. The difference is probably dominated by the contrast in tectonic setting between terrestrial thrust faults and those on Mercury and Mars. The similarity in morphology and the D-L relationship of the mercurian and martian thrust faults may be due to the similarity in mechanical properties of the deformed materials and the acceleration due to gravity of the two planets.

1. Introduction

Lobate scarps are distinctive landforms found on Mercury and Mars that are thought to be the surface expressions of thrust faults based on their morphology, and because where they cross impact craters the walls and floors of these craters are offset [*Strom et al.*, 1975; *Cordell and Strom*, 1977; *Watters et al*, 1998; *Watters and Robinson*, 1999] (Figure 1). Until recently, detailed studies of lobate scarps on Mercury and Mars have been limited by a lack of sufficient topographic data. Using newly recalibrated Mariner 10 images [*Robinson and Lucey*, 1997] and updated Mariner 10 camera orientations and improved geometric rectification [*Robinson et al.*, 1999] it is now possible to obtain reliable topographic data for mercurian lobate scarps with photoclinometry and digital stereoanalysis [*Watters et al.*, 1998]. Photoclinometry, where topography along a selected profile is determined by comparing brightness variations between adjacent pixels, has been used successfully to derive topographic data from Viking Orbiter images of Mars [see *Davis and Soderblom*, 1984; *Watters and Robinson*, 1997, 1999]. The Mars Orbiter Laser Altimeter (MOLA) is a new source of topographic data [*Smith et al.*, 1998; *Zuber et al.*, 1998]. These data have a maximum vertical resolution of ~30 cm, an absolute vertical accuracy of ~30 m, and along-track spatial resolution of 300 to 400 m [*Smith et al.*, 1998].

The largest known lobate scarp on Mercury is Discovery Rupes [*Strom et al.*, 1975]. This structure has a measured relief of ~1.5 km and is continuous over its more than 500 km length (Figure 1A) [*Watters et al.*, 1998]. Discovery Rupes transects two large impact craters, deforming the walls and offsetting crater floor materials. Because of cross-cutting relationships with large craters, lobate scarps like Discovery Rupes are thought to have formed after the period of heavy bombardment (about 4 Gyr ago) [*Melosh and McKinnon*, 1988]. One of the largest and best preserved martian lobate scarps is Amenthes Rupes (Figure 1B, 2). It is over 400 km

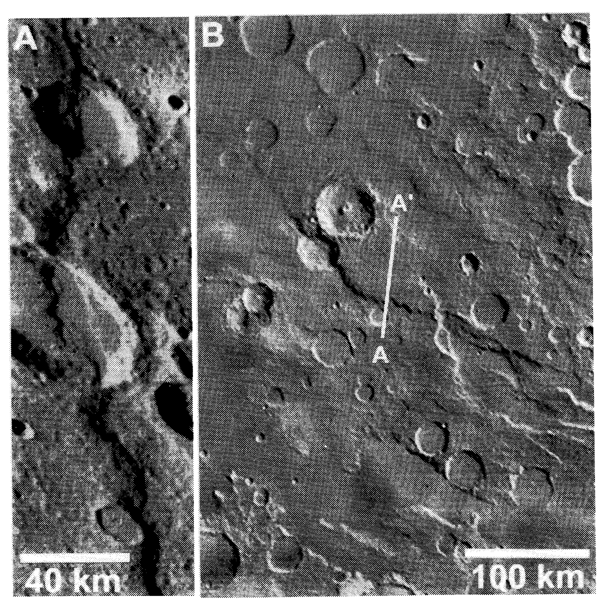

Figure 1. (A) Mariner 10 image of Discovery Rupes, largest known lobate scarp on Mercury (frame # 0528884). (B) Viking Orbiter mosaic of Amenthes Rupes, one of the largest lobate scarps on Mars. These thrust faults cut the walls and floors of impact craters.

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long with a measured relief of ~1.2 km [*Watters and Robinson*, 1999], comparable in scale to Discovery Rupes. Martian lobate scarps appear to have formed during the Late Noachian and Early Hesperian [*Tanaka et al.*, 1991; *Watters and Robinson*, 1999], after the martian period of heavy bombardment.

A new paradigm in fault mechanics has emerged over the last decade based on analysis of terrestrial faults, the maximum displacement D on a fault scales with the planimetric length of the fault L [*Walsh and Watterson*, 1988; *Cowie and Scholz*, 1992; *Cartwright et al.*, 1995]. This relationship also holds for planetary faults [*Schultz*, 1997, 1999; *Watters et al.*, 1998; *Watters and Robinson*, 1999]. D and L are related by $D = cL^n$, where c is a constant related to material properties and n is the power-law exponent [*Walsh and Watterson*, 1988]. Detailed studies of terrestrial faults in populations formed in uniform rock types, however, support a linear relationship $D = \gamma L$, where γ is a constant determined by rock type and tectonic setting (and $n = 1$) [see *Cowie and Scholz*, 1992; *Clark and Cox*, 1996]. Evidence also suggests that the scaling relationship between D and L generally holds for all the fault types (i.e., normal, strike-slip, and thrust) in a wide variety of tectonic settings and eight orders of magnitude in length scale [*Cowie and Scholz*, 1992]. The ratio of maximum displacement to fault length γ for the fault populations ranges between 10^0 and 10^{-3}. Scatter in the D-L data can arise from several sources including fault segmentation, uncertainties in fault dip and depth (aspect ratio), interaction with other faults, and ambiguities in determining D along the scarp trace [*Cartwright et al.*, 1995, *Dawers and Anders*, 1995; *Wojtal*, 1996; *Schultz*, 1999].

2. Results

Displacement is estimated by assuming it is a function of the relief of the lobate scarp and the dip of the surface-breaking fault-plane. Given the measured relief of the scarp h and the fault-plane dip θ, the displacement necessary to restore the topography to a planar surface is given by $D = h/\sin\theta$ (Figure 2) [also see *Wojtal*, 1996]. Of the two variables, the larger uncertainty is in the fault-plane dip. The optimum angle θ at which faulting will occur, the angle for which the differential horizontal stress necessary to initiate faulting is a minimum, is given by $\tan 2\theta = 1/f_s$ where f_s, is the coefficient of static friction [*Jaeger and Cook*, 1979; *Turcotte and Schubert*, 1992]. Using a range in f_s of 0.6 to 0.9 based on laboratory data on the maximum shear stress to initiate sliding for a given normal stress (best fit $f_s = 0.85$) [*Byerlee*, 1978], thrust faults with dips from about 24° to 30° are likely. This is generally consistent with field observations of θ [*Sibson*, 1996] for thrust faults that typically range between 20 to 25° [see *Jaeger and Cook*, 1979]. Thrust faults in the Rocky Mountain foreland in Wyoming have dips between 25° and 30° [*Gries*, 1983; *Stone*, 1985], and the large-scale Wind River thrust fault has an average dip of 35° [*Brewer et al.*, 1980]. We infer that the thrust faults associated with lobate scarps have fault-plane dips ranging from 20° to 35°. It is also assumed that fault planes have generally uniform dips that do not significantly curve or bend. Here again, the thrust faults of the Rocky Mountain foreland in Wyoming are good examples of terrestrial thrust faults with uniform dips [*Brewer et al.*, 1980; *Gries*, 1983; *Stone*, 1985] (although some do steepen upward where they cut Paleozoic sedimentary sequences [*Stone*, 1985]). Thrust faults having non-uniform dips are commonly found on Earth in orogenic fold-and-thrust belts [e.g., *Elliott*, 1976a, b].

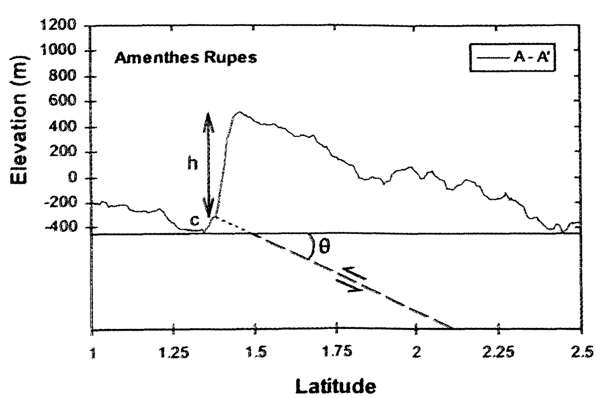

Figure 2. MOLA profile across Amenthes Rupes. The maximum relief (h) and the hypothetical fault-plane dip (θ) are shown, but not the total depth extent of the fault. The MOLA profile shown in Figure 1B (A – A') crosses an impact crater (c) located at the base of the scarp (see Figure 1B). These data were extracted from orbit 10636. Elevations are relative to a reference potential surface and the vertical exaggeration is ~24:1.

Estimates of D on mercurian and martian thrust faults were determined using measurements of the relief of the lobate scarps from topography obtained from photoclinometry, stereoanalysis, and MOLA (see Supplemental Table[1]). Displacement on the mercurian thrust faults studied range from 0.29 to 1.95 km, assuming fault-plane dips of 25°, with an average of ~0.86 km ($n = 9$). The maximum displacement on the Discovery Rupes thrust fault is on the order of 2.64 to 4.43 km for a θ of 20° and 35° respectively and ~3.58 km for $\theta = 25°$. Maximum displacements for the martian thrust faults studied range from 0.27 km to 1.62 km, with an average of ~0.75 km for $\theta = 25°$ ($n = 12$). These faults occur in the highlands of Amenthes and northern Terra Cimmeria, northern Arabia Terra, and Noachis Terra. The maximum displacement on the Amenthes Rupes thrust fault is on the order of 2.14 to 3.58 km for $\theta = 20°$ and 35° respectively and ~2.90 km for $\theta = 25°$.

Values for maximum displacements and fault lengths for the mercurian and martian lobate scarps studied span two orders of magnitude. The values of γ for these two populations of thrust faults were obtained by a least-squares fit to the D-L data with the intercept set to the origin [see *Cowie and Scholz*, 1992]. The γ for the mercurian lobate scarps, using estimates of D based on $\theta = 25°$, is $6.5 \pm 3.2\times10^{-3}$ ($n = 10$) (the uncertainty is the standard deviation of γ for these faults determined for $\theta = 28°$, the average of the assumed range of fault-plane dips) (Figure 3). The γ for the martian lobate scarps, also based on $\theta = 25°$, is $5.9 \pm 2.0\times10^{-3}$ ($n = 13$) (Figure 3).

[1]Supporting material is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

3. Discussion

The values of γ determined for mercurian and martian lobate scarps are comparable to values of γ of terrestrial fault populations [*Cowie and Scholz*, 1992]. However, the displacements on the faults associated with the mercurian and martian lobate scarps are about an order of magnitude lower than particular terrestrial thrust faults plotted in Figure 3. These thrust faults occur in the foreland thrust belt of the Canadian Rocky Mountains, with the *D-L* values compiled by *Elliott* [1976a] (see *Cowie and Scholz* [1992]). Here Paleozoic sedimentary rocks are cut by a series of imbricate thrust faults rooted in a basal décollement that separates the deformed sequence from the undeformed basement [*Elliott*, 1976b]. The contractional strain across the thrust belt is estimated to be as much as 83% [*Elliott*, 1976b]. For comparison, the Wind River thrust fault (Figure 3) has a map length of ~220 km and extends to a depth of 36 km with perhaps 21 to 30 km of displacement [*Brewer et al.*, 1980] (M.H. Anders, personal communication, 1998), leading to a value of γ of $\sim 1.4 \times 10^{-1}$. Given the uncertainties in the quality of data from the terrestrial thrust fault sets [e.g., *Cowie and Scholz*, 1992], the maximum displacement on the Wind River thrust fault falls in the range of the imbricate thrust faults. The most likely explanation for the order of magnitude difference in displacements between the terrestrial and planetary thrust faults is tectonic setting. The terrestrial thrust faults occur in foreland thrust belts located at convergent plate margins where the structures accumulate large amounts of strain and the deformation is driven by plate tectonics. By contrast, the lobate scarps on Mercury and Mars are isolated structures that reflect more distributed deformation. It is likely that the contrast in tectonic setting dominates other factors influencing the growth of the thrust faults such as differences in acceleration due to gravity or differences in mechanical properties.

The similarity in γ between mercurian and martian thrust faults may itself reflect a similarity in mechanical properties of the materials and the gravity of the two planets. Thrust

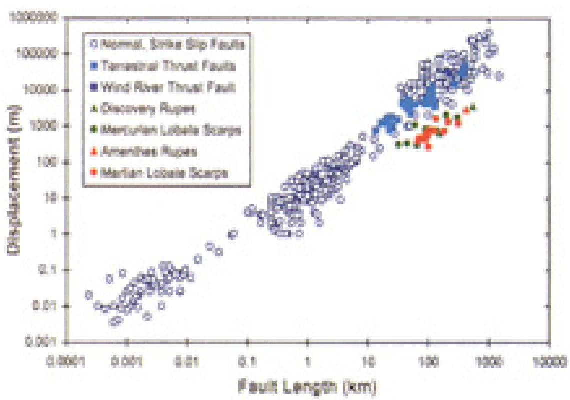

Figure 3. Log-log plot of maximum displacement as a function of fault length for terrestrial faults, Discovery Rupes and 9 other mercurian lobate scarps, and Amenthes Rupes and 12 other martian lobate scarps (see legend). The data for terrestrial faults are from 9 different data sets [*Cowie and Scholz*, 1992] and include thrust faults in the foreland thrust belt of the Canadian Rocky Mountains ($\gamma = 8.0 \times 10^{-2}$, $n = 29$) and the Wind River thrust fault in the Rocky Mountain foreland of Wyoming.

faulting can occur at fault-plane dips θ that minimize the horizontal stress. The minimum horizontal stress necessary to initiate faulting may be given by

$$\Delta\sigma_{xx} = \frac{2 f_s (\rho g z)}{(1 + f_s^2)^{1/2} + f_s} \qquad (1)$$

where f_s is the coefficient of maximum static friction, ρ is the average crustal rock density, g is the acceleration due to gravity, and z is the depth [*Turcotte and Schubert*, 1992]. This suggests that if f_s and ρ are similar on Mercury and Mars, thrust faulting will occur to about the same depth given the similarity in the acceleration due to gravity ($g_{\mathrm{Mars}} = 3.72$ m/s^2, $g_{\mathrm{Mercury}} = 3.78$ m/s^2) because the compressional strength of the upper crust of both planets is nearly equal.

Mercurian lobate scarps are thought to have resulted from either global contraction due to secular cooling of the interior, tidal despinning, or a combination of the two [*Strom et al.*, 1975; *Cordell and Strom*, 1977; *Melosh and Dzurisin*, 1978; *Melosh and McKinnon*, 1988]. Global contraction due to a small change in the radius of the planet is favored, however, because tidal despinning models predict a system of normal faults at Mercury's poles that have not been observed. The magnitude of the horizontal compressional stresses that result from a change ΔR in the radius of a sphere R is given by

$$\sigma_{\theta\theta} = \sigma_{\phi\phi} = 2\mu \left(\frac{1 + \nu}{1 - \nu} \right) \frac{\Delta R}{R} \qquad (2)$$

where $\sigma_{\theta\theta}$ is the meridional (N-S) and $\sigma_{\phi\phi}$ is the azimuthal (E-W) stress component, ν is Possion's ratio, and μ is the shear modulus which is given by

$$\mu = \frac{E}{2(1 + \nu)} \qquad (3)$$

where E is the Young's modulus [*Melosh and McKinnon*, 1988]. A radius change of 2 km, the upper limit estimated by *Strom et al.* [1975], corresponds to compressional stresses of about 109 MPa (~1 kbar), assuming E = 100 GPa for the lithosphere of Mercury. If the upper limit is more on the order of 1 km [*Watters et al.*, 1998], then the corresponding stresses are ~55 MPa.

With a compressional stress of approximately 60 to 100 MPa and assuming $f_s = 0.85$, thrust faults on Mercury would be expected to penetrate to depths of as much as 3 km (eq. 1). Thus stresses resulting from global contraction may produce thrust faulting of the uppermost crust of Mercury, although the faulting may have initiated at shallow depths and propagated to greater depths as the faults accumulated displacement. If the faults are more deeply rooted, stresses resulting from global contraction may have been only one component of the total stress state that formed the thrust faults.

The origin of the stresses that formed martian lobate scarps is not well understood. *Tanaka et al.* [1991] suggest that global contraction during the Late Noachian/Early Hesperian formed lobate scarps in the highlands as well as wrinkle ridges across smooth plains materials. On the other hand, many martian lobate scarps occur near and are orientated parallel to the crustal dichotomy boundary, a geologic and topographic transition between the southern heavily cratered highlands and the northern lowlands. This suggests that these thrust faults may be related to the formation or development of the dichotomy boundary [*Watters and Robinson*, 1999]. On Mars, by analogy with their mercurian counterparts, the thrust faults associated with lobate scarps should also penetrate through at least the upper few kilometers of the lithosphere. If, for example, the horizontal stresses that formed the martian thrust faults were on the order of 100 MPa, the depth of faulting would be ~2.5 km (eq. 1). As with thrust faulting on Mercury, faults may penetrate to greater depths, particularly faults associated with large-scale lobate scarps like Amenthes Rupes.

Little is known about the material properties of the principal units on Mercury. Many of the mercurian lobate scarps occur in units described as intercrater plains (see Figure 1A). Intercrater plains occur in and around ancient cratered terrain, the oldest exposed unit on Mercury [*Trask and Guest*, 1975; *Spudis and Guest*, 1988]. The intercrater plains are thought to be either volcanic or impact in origin, although there is no definitive evidence supporting either interpretation [see *Spudis and Guest*, 1988]. If the intercrater plains are composed of ejecta material, they may consist of a sequence of intercalated facies of impact basin ejecta [*Trask and Guest*, 1975; *Spudis and Guest*, 1988].

Martian lobate scarps, like their counterparts on Mercury, occur in intercrater plains in the heavily cratered highlands (Figure 1B) [*Watters*, 1993; *Watters and Robinson*, 1999]. Recently, our understanding of the nature of the martian heavily cratered highlands has changed dramatically. Mars Orbiter Camera (MOC) images have revealed layering, to depths of at least 5 to 10 km in at least one region, in units that had been thought to be a megaregolith consisting of impact breccias [*Malin and Edgett*, 1999; *McEwen*, 1999; *McEwen et al.*, 1999]. It has been hypothesized that layered intercrater plains are made up of a combination impact ejecta and volcanic flows, and possibly sedimentary deposits [*McEwen*, 1999]. Although the depth to which layering in the highlands extends is not known, thrust faults cut and may have initiated in layered sections of the highlands.

Thus, the first-order mechanical properties of the intercrater plains on Mercury and the heavily cratered highlands of Mars may be similar. This and the nearly identical acceleration due to gravity of the two planets may account for the similarity in morphology and γ values between the mercurian and martian thrust faults. The similarity in the scaling of thrust faults on Mercury and Mars also suggests that the cumulative moment release and strain associated with thrust faulting is similar for both planets.

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References

Brewer, J.A., S.B. Smithson, J.E. Oliver, S. Kaufman, and L.D. Brown, The Laramide orogeny: Evidence form COCORP deep crustal seismic profiles in the Wind River mountains, Wyoming, *Tectonophysics, 62*, 165-189, 1980.

Cartwright, J.A., B.D. Trudgill, and C.S. Mansfield, Fault growth by segment linkage: An explanation for scatter in maximum displacement and trace length data from the Canyonlands Grabens of SE Utah, *J. Struct. Geol., 17*, 1319-1326, 1995.

Clark, R., and S. Cox, A modern regression approach to determining fault displacement-length scaling relationships, *J. Struct. Geol., 18*, 147-154, 1996.

Cordell, B.M., and R.G. Strom, Global tectonics of Mercury and the Moon, *Phys. Earth Planet. Inter., 15*, 146-155, 1977.

Cowie, P.A., and C.H. Scholz, Displacement-length scaling relationship for faults: Data synthesis and discussion, *J. Struct. Geol., 14*, 1149-1156, 1992.

Davis, P.A., and L.A. Soderblom, Modeling crater topography and albedo from monoscopic Viking Orbiter images, *Icarus,* 89, 9449-9457, 1984.

Dawers, N.H., and M.H. Anders, Displacement-length scaling and fault linkage, *J. Struct. Geol., 17*, 607-614, 1995.

Elliott, D., The energy balance and deformation mechanisms of thrust sheets, *Phil. Trans. R. Soc. Lond., A283*, 289-312, 1976a.

Elliott, D., The motion of thrust sheets, *J. Geophys. Res., 81*, 949-963, 1976b.

Gries, R., Oil and gas prospecting beneath Precambrian of foreland thrust plates in Rocky Mountains, *Am. Assoc. Petrol. Geol. Bull., 67*, 1-28, 1983.

Jaeger, J.C., and N.G.W. Cook, *Fundamentals of Rock Mechanics*, 3rd ed., 593 pp., Chapman and Hall, London, 1979.

Malin, M.C., and K.S. Edgett, An emergent, new paradigm for Mars geology (abstract), *5th Mars Colloquium,* 6027, 1999.

McEwen, A.S., Stratigraphy of the upper crust of Mars (abstract), *5th Mars Colloquium,* 6024, 1999.

McEwen, A.S., M.C. Malin, M.H. Carr, and W.K. Hartmann, Voluminous volcanism on eartly Mars revealed in Valles Marineris, *Nature, 397*, 584-586, 1999.

Melosh, H.J., and D. Dzurisin, Mercurian global tectonics: A consequence of tidal despinning?, *Icarus, 35*, 227-236, 1978.

Melosh, H.J., and W.B. McKinnon, The tectonics of Mercury, in *Mercury*, edited by F. Vilas, C.R. Chapman, and M.S. Matthews, 374-400, 1988.

Robinson, M.S., and P.G. Lucey, Recalibrated Mariner 10 color mosaics: Implications for mercurian volcanism, *Science, 275,* 197-200, 1997.

Robinson, M.S., M.E. Davies, T.R. Colvin, K.E. Edwards, A revised control network for Mercury, *J. Geophys. Res., 104,* 30847-30852, 1999.

Schultz, R.A., Displacement-length scaling for terrestrial and Martian faults: Implications for Valles Marineris and shallow planetary grabens, *J. Geophys. Res., 102,* 12009-12015, 1997.

Schultz, R.A., Understanding the process of faulting: Selected challenges and opportunities at the edge of the 21st century, *J. Struct. Geol., 21,* 985-993, 1999.

Sibson, R.H., An assessment of field evidence for 'Byerlee' friction, *Pure Appl. Geophys., 142*, 645-662, 1996.

Stone, D.S., Geologic interpretation of seismic profiles, Big Horn Basin, Wyoming, Part I: East Flank, in *Seismic Exploration of the Rocky Mountain Region*, edited by R.R. Gries and R.C. Dyer, pp. 165-174, Rocky Mountain Association of Geologists, 1985.

Strom, R.G., N.J. Trask, and J.E. Guest, Tectonism and volcanism on Mercury, *J. Geophys. Res., 80*, 2478-2507, 1975.

Tanaka, K.L., M.P. Golombek, and W.B. Banerdt, Reconciliation of stress and structural histories of the Tharsis region of Mars, *J. Geophys. Res., 96*, 15,617-15,633, 1991.

Turcotte, D.L. and G. Schubert, *Geodynamics*: Application of Continuum Physics to Geological Problems, 450 pp., John Wiley, New York, 1982.

Watters, T.R., Compressional tectonism on Mars, *J. Geophys. Res., 98*, 17049-17060, 1993.

Watters, T.R. and M.S. Robinson, Radar and photoclinometric studies of wrinkle ridges on Mars, *J. Geophys. Res., 102,* 10889-10903, 1997.

Watters, T.R. and M.S. Robinson, Lobate scarps and the origin of the Martian crustal dichotomy, *J. Geophys. Res., 104*, 18981-18990, 1999.

Watters, T.R., M.S. Robinson, and A.C. Cook, Topography of lobate scarps on Mercury: New constraints on the planet's contraction, *Geology, 26*, 991-994, 1998.

Walsh, J., and J. Watterson, Analysis of the relationship between displacements and dimensions of faults, *J. Struct. Geol., 10*, 239-247, 1988.

Wojtal, S.F., Changes in fault displacement populations correlated to linkage between faults, *J. Struct. Geol., 18*, 265-279, 1996.

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