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Is the Gordii Dorsum escarpment on Mars an exhumed transcurrent fault?

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Investigators of deformation features on the surface of Mars have generally concluded that fault zones with major horizontal displacements do not occur or have not been preserved[1–5]. Here we present evidence from high-resolution Viking imagery for an array of structures along the Gordii Dorsum escarpment which suggest that it is a left-lateral strike-slip fault zone of lithospheric proportion. The escarpment is one of an array of subparallel ridges[6,7] preserved in an equatorial region to the west of Tharsis Montes. The region is of transitional character between the youthful ('Amazonian' age) cover of the Amazonia Planitia to the north and older ('Noachian' age) intensely cratered surfaces of the Highlands to the south. Relations between these ridges and the Gordii Dorsum suggest that the ridges are exhumed ancient fault zones. These features imply that Mars, like the Earth today, may have had in its early stages a more dynamic tectonic style of planetary evolution.

Ancient strike-slip faults on Mars could be difficult to identify. Their traces may readily be masked by later cratering, volcanism or aeolian erosion and redeposition. Also, where strike-slip faults at depth are covered by poorly consolidated strata, deformation at the surface is likely to be distributed over a broad zone of shearing with or without the development of a surface-breaking strike-slip fault[8,9]. In these situations characteristic secondary deformation structures commonly develop in the cover strata[8,9], but such features would not be easily identified on the low- to moderate-resolution imagery that has been the basis of much of the earlier tectonic studies of the surface of Mars.

Here we present evidence for a set of secondary tectonic features along the Gordii Dorsum escarpment, which are believed to be related to a major left-lateral fault in the lithosphere. The escarpment, with 100-400 m of relief (shadow-length estimates), has been interpreted previously[10–12] as a ~500-km-long normal fault with the east-northeastern side displaced downwards with respect to the west-southwestern side, according to Mariner 9 and Viking data with poor (1-km) to moderate (200-m) resolution. Near the end of the Viking Orbiter 1 mission, a series of high-resolution (35 m per pixel) vidicon images were obtained for the southeastern portions of the Amazonia Planitia, and these images provide excellent coverage of the southern 290 km of the Gordii escarpment. These images were spatially filtered, to emphasize surface relief and minimize albedo variations, and were assembled manually into a map. A strip, marginal to the escarpment (0°–8° N, 138–148° W, orbits 462S–467S), of width ~80 km, was extracted from the overall mosaic map for this structural investigation (Fig. 2).

On the regional scale the Gordii Dorsum forms a boundary between provinces of contrasting geological character. To the ENE, along the depression flanking the escarpment, sparsely cratered (51 craters with diameters >0.6 km over ~9,000 km^2), but otherwise undeformed, strata (terrain II, Fig. 2) cover a highly lineated basement terrain (IV) which is visible in erosional windows and in localized basement highs along the base of the escarpment. The cover strata, mapped as Amazonian-age volcanic flow units which were probably erupted from Arsia Mons[10,12], exhibit highly irregular cuestas, extensive regions of mottled ground, and pedestal craters. The escarpment appears to have acted as a structural dam to these flows.

To the WSW a thicker sequence of cover (terrain I) has been uplifted (relative to ENE side) and exposed along a structurally controlled NNW-trending series of cuestas. In contrast to the northeastern side, over the 16,000 km^2 of terrain I there is a conspicuous lack of craters, and exposures of the deeper stratigraphic levels exhibit an east–west, rather than NNW, linear grain. Here youthful exhumation of an older surface appears to be the only mechanism that can adequately explain how the deformed, but uncratered, surface deposits of terrain I are embayed by undeformed, but cratered, units seen at the base of the escarpment in terrain II.

To the SSE a third region has surface materials that overlap the Gordii Dorsum escarpment without any signs of deformation. Here, the subdued ridge-and-pinnacle topography is suggestive of an ablated, but previously intensely cratered, surface[13,14]. This region is transitional to terrain I, with the gradual appearance of a structurally controlled cuesta morphology and the disappearance of the ridge-and-pinnacle morphology. Terrain III also seems to be embayed by the cover units of terrain II. These relations imply that the cratered surface of terrain III developed after faulting but before exhumation of terrain I.

Within a 40–50-km fringe on the upwardly displaced side of the escarpment, cuestas and undulations of the surface of terrain I constitute records of gentle folding and/or faulting along subparallel trends to the escarpment. In Fig. 3*a* there appears to be a gentle, doubly-plunging anticline where the axial culmination is breached by aeolian erosion, and deeper, but exposed, layers show gradual shifts in albedo as they gradually change dip over the fold structure. Elsewhere, there are local undula-

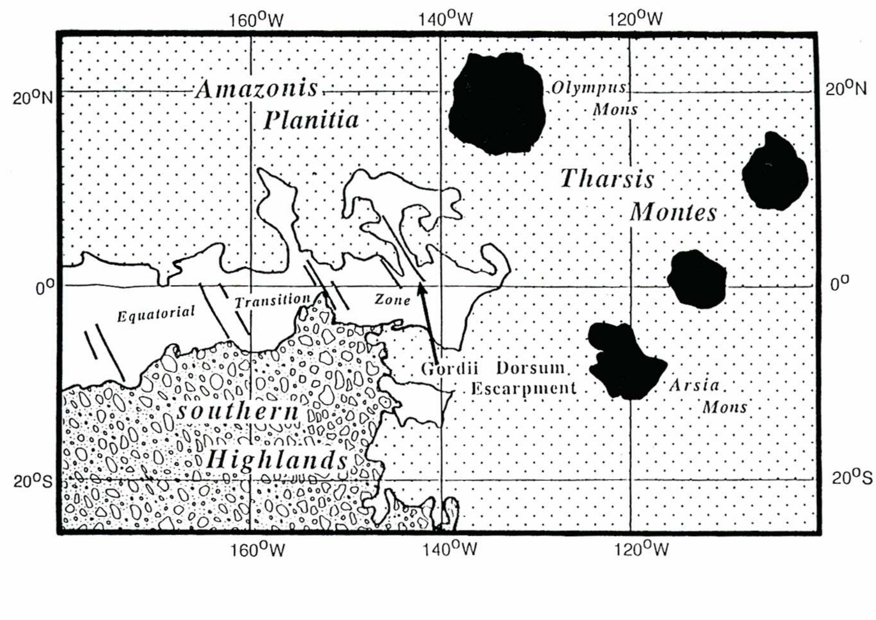

Fig. 1 Location and terrain map for the study area in the equatorial zone of Mars, to the west of the Tharsis Montes. Shown in black are the main volcanic edifices; in 'breccia' pattern, the intensely cratered ancient Noachian surfaces most typical of the highlands of the southern hemisphere; and in white, the transitional areas, suggested to be intermediate in age (Hesperian) between that of the Highlands areas and of the younger (Amazonian) materials that dominate the northern hemisphere (stippled). Many subdued and linear ridges trend NNW, parallel to the Gordii Dorsum escarpment, but these are largely restricted to the equatorial transition area.

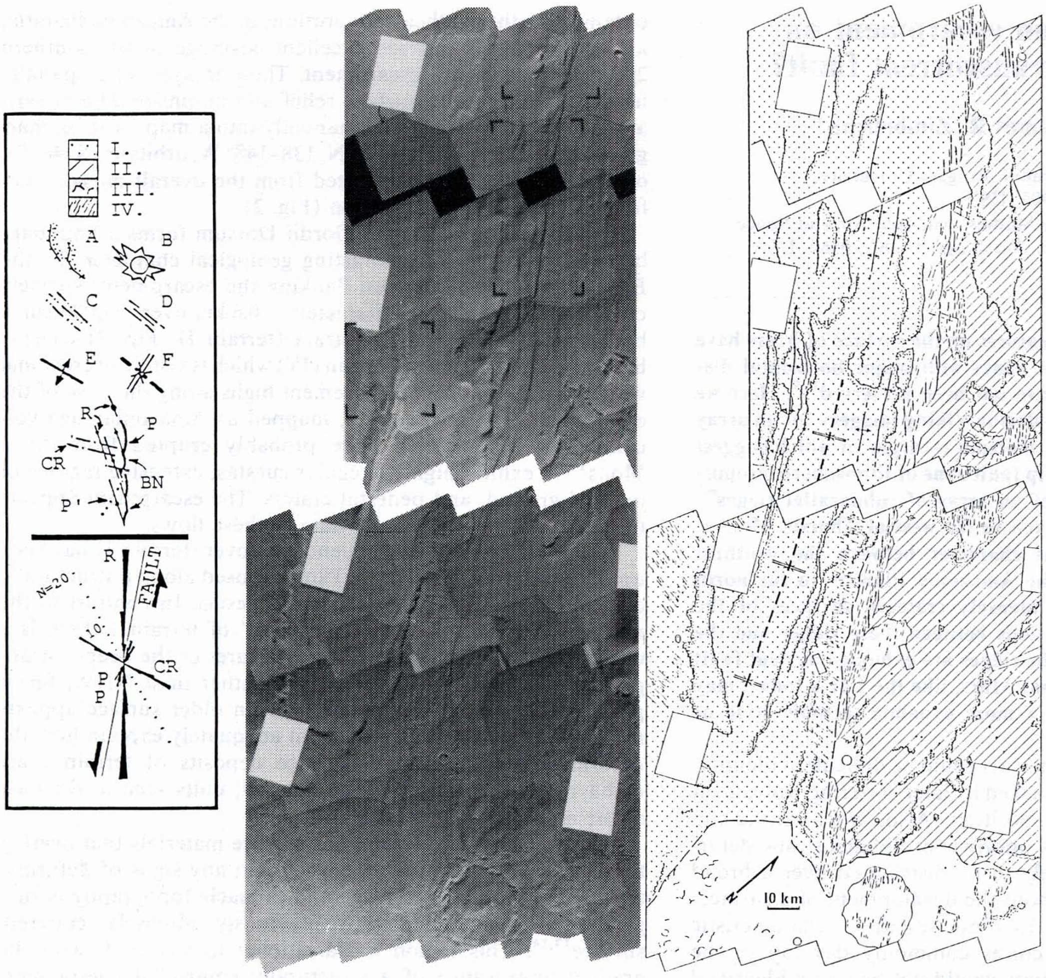

Fig. 2 Viking image mosaic and geological interpretation for a region along the central parts of the Gordii Dorsum escarpment (here interpreted as a left-lateral transcurrent fault). Terrains represent: I, uplifted rolling plains of deeply exhumed, uncratered but deformed strata, probably of Noachian to early Hesperian age; II, sparsely cratered, but undeformed lava (?) plains, probably of Amazonian age; III, moderately exhumed but intensely cratered surface with ridge-and-pinnacle morphology, probably of Noachian age; IV, erosional windows of a highly lineated basement. Symbols are: A, cuestas; B, pedestal craters; C, semi-pervasively linear ground; D, discretely linear ground; E, axial trace of gentle fold; F, general axis of downwarp; R, Reidel shears; CR, conjugate Reidel shears; BN, 'bullnose' structures; P, P-shears; and P′, P′-shears (discussed in text).

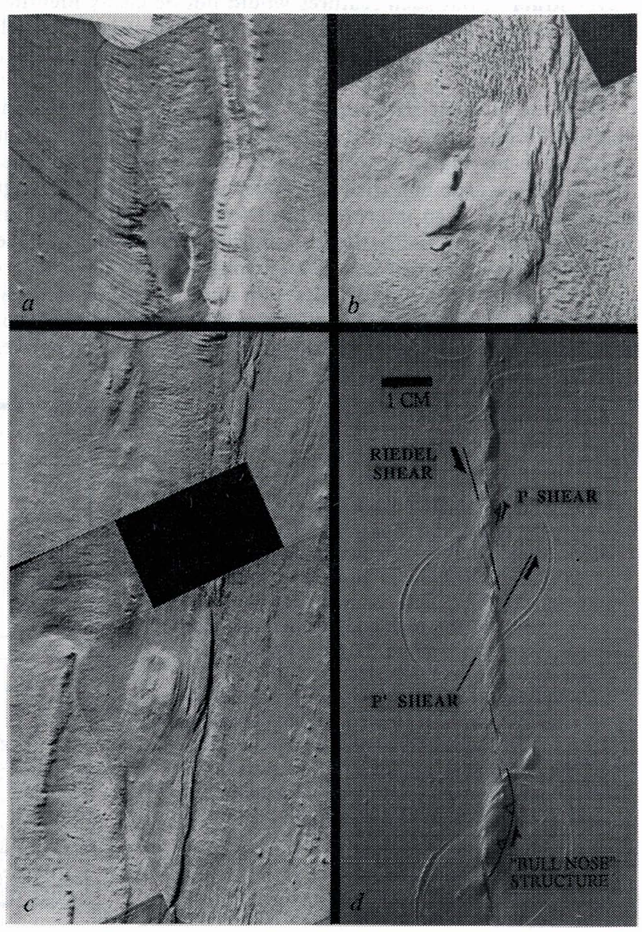

Fig. 3 *a*, Close-up of region of anticlinal folding, showing differential aeolian erosion along axial culmination and gradual albedo shifts on the folded layers. *b*, Close-up image of the north-northwesternmost part of the escarpment, where two prominent sets of highly linear surface features are preserved along the upwardly displaced side. These have angular relations (illustrated in Fig. 2), interpreted as the same as the Reidel and conjugate Reidel shears for left-lateral faults. *c*, Close-up of region of en echelon 'push-up' structures along the Gordii Dorsum escarpment; each appears localized by prominent NNW-trending linear features here interpreted as the primary Reidel shears along a left-lateral fault. *d*, Clay-drape experiment mimicking three of four synthetic shears on the Gordii Dorsum fault zone, and the push-up or 'bullnose' structures along the southwestern upthrown side.

tions which appear to be more step-like.

In the 15-20-km fringes of the escarpment there are four sets of linear features, which are comparable with the arrays of staggered synthetic and antithetic shears that are found along major left-lateral fault zones on Earth and in laboratory clay-drape shear experiments[8,9]. Three of these are known as Reidel, conjugate Reidel and P-shears. The angular relations (rose diagram in lower inset of Fig. 2) for the main Reidel shears (that is, arrays of staggered left-lateral microfaults) are the same as those seen in laboratory left-lateral shear experiments. Lineaments that probably correspond to the conjugate Reidel (arrays of staggered right-lateral microfault) shears can be discerned only in the NNW portion (Fig. 3*a*), where the angle made with the fault zone (70-80°) is somewhat lower than those found in experiments, but is not atypical of what has been found in real geological systems[8]. The escarpment itself is formed of a series of en echelon (staggered) north-south trending segments bounded to the NNW and SSE by prominent Reidel shears (Figs 3*a* and *b*). Each of these segments forms a conspicuous bulge along the escarpment and gives it a scalloped appearance in map view. The angular and spatial relations of these segments are the same as that described for the P-shears in the experiments. P-shears are the terminations of prominent Reidel shears that accommodate components of reverse faulting in the progressive stages of shearing during which a through-going fault zone is formed. The result is an en echelon series of bulges or push-up structures, called 'bull-nose' structures in reports on clay-drape experiments[8] and 'positive flower' structures in the petroleum industry[15,16]. A fourth linear structure, here labelled the P′-shear (subparallel to the P-shear), has not been documented in previous clay-drape shear laboratory experiments. We have performed similar experiments, however, using soft (>40% H_2O) and thin (<1.5-cm) clay layers, in which, following P-shear development, internal shortening of the 'push-up' was accommodated in the late stages by the development of high-angle synthetic shears (P′-shears) which essentially imbricate the push-up in plan view (Fig. 3*c*).

In the laboratory experiments[8], resistance to shear across the fault zone peaks during the development of the maximum width of the zone affected by the Reidel shears, and then is quickly reduced, with continued shearing, as the deformation collapses by P-shear formation into a zone more restricted to the trace of the basement fault[8]. In these experiments cumulative displacements up to the development of P-shears usually involves amounts equal to, or greater than, the width of the zone affected by the Reidel shears. The complete array of features seen along the Gordii Dorsum escarpment indicate that this fault zone has evolved to post-peak shear stress stages. Thus, by analogy, we can argue crudely for a minimum left-lateral displacement roughly equal to the width of the zone affected by the Reidel shears. These are exhumed only in the 15-20-km fringe on the upwardly displaced side. Because the downwardly displaced block appears to be buried by younger cover deposits, we are forced to assume a symmetric relationship and to infer a minimum left-lateral displacement of about 30-40 km, which is one to two orders of magnitude greater than the minimum dip-slip motion.

Based on relations seen between terrains I, II and III, the faulting probably occurred before cratering of terrain III. Terrain III has been mapped previously as comprising Hesperian-age surface materials typical of the western equatorial transition zone[2,10-12]. We argue here, however, that ablation of the surface is quite extensive, and that the surface of terrain III appears to grade gradually into the exhumed uncratered surface of terrain I. Thus it seems most probable that the local crater densities are not so much indicative of the age of surface units but more probably of minimum ages for surface modification. The most logical alternative is that the surface of terrain III is representative of upper Hesperian (or younger) modifications of a lower Hesperian (or older) cratered surface. We suggest that this cratering postdates the faulting, which implies that the faulting is very ancient, probably of Noachian or early Hesperian age.

Although the data presented here for the Gordii Dorsum escarpment do not invalidate the evidence for lithospheric immobility in the greater part of the geological history of Mars, they do suggest that an earlier phase of lithospheric mobility has not been completely obliterated.

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1. Basaltic Volcanism Study Project *Basaltic Volcanism of the Terrestrial Planets* (Pergamon, New York, 1981).
2. Scott, D. H. & Carr, M. H. *U.S. geol. Surv. Map I-1083* (USGS, Denver, 1978).
3. Wise, D. U., Golombek, M. P. & McGill, G. E. *Icarus* **38**, 456-472 (1979).
4. Phillips, R. J. & Ivins, E. R. *Phys. Earth planet. Inter.* **19**, 107-148 (1979).
5. Golombek, M. *J. geophys. Res.* **90**, 3065-3074 (1985).
6. *U.S. geol. Surv. Map I-1535, 1:15M Shaded Relief* (USGS, Denver, 1985).
7. *U.S. geol. Surv. Map I-1333 1:2M* (USGS, Denver, 1981).
8. Tchalenko, J. S. *Geol. Soc. Am. Bull.* **81**, 1625-1640 (1970).
9. Wilcox, R. E., Harding, T. P. & Seely, D. R. *Bull. Am. Ass. Petrol. Geol.* **57**, 74-96 (1973).
10. Scott, D. H. & Tanaka, K. L. *J. geophys. Res.* **87**, 1179-1190 (1982).
11. Schaber, G. E., Horstman, K. C., Dial, A. L. Jr, Scott, D. H. & Tanaka, K. C. *U.S. geol. Surv. Map I-1280* (USGS, Denver, 1982).
12. Morris, E. C. & Dwornik, S. E. *U.S. geol. Surv. Map I-1049* (USGS, Denver, 1978).
13. McCauley, J. F. *et al. Icarus* **17**, 289-327 (1978).
14. Carr, M. H. *U.S. geol. Surv. Map I-893* (USGS, Denver, 1975).
15. Harding, T. P. & Lowell, J. D. *Bull. Am. Ass. Petrol. Geol.* **63**, 1016-1058 (1979).
16. Harding, T. P. *Bull. Am. Ass. Petrol. Geol.* **69**, 582-600 (1985).