System of tectonic features common to Earth, Mars, and Venus

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ABSTRACT

Investigations of landforms on the terrestrial planets have revealed a system of tectonic features consisting of long, narrow, regularly spaced folds and/or thrust faults, referred to as wrinkle ridges, and conjugate sets of cross-trending strike-slip faults. These are observed in the Yakima fold belt of the Columbia Plateau, Earth, the ridged plains of the Tharsis province, Mars, and the lowland plains of Lavinia Planitia, Venus. The wrinkle ridges and strike-slip faults reflect a relatively small amount of crustal shortening in these regions of distributed deformation. The observed geometric relations between the structures are consistent with those predicted by the Coulomb-Anderson model. Although the tectonic settings of the provinces studied on the three planets are very different, the crustal materials appear to have deformed in a similar manner.

INTRODUCTION

Areas of crustal convergence and shortening on Earth are often characterized by structural domains where folds and thrust faults are associated with conjugate sets of cross-trending strike-slip faults (see Sylvester, 1988). This tectonic system is common in foreland fold-thrust belts, such as the Asiak of northern Canada (Hoffman et al., 1984), and deformed accretionary prisms, such as the Shumagin region of the Aleutian trench (Lewis et al., 1988) and the Makran of southwest Pakistan (Platt et al., 1988). Domains of crustal shortening are also evident on the other terrestrial planets. Large expanses of smooth plains materials, known to be flood basalts on the Moon and suspected to be volcanic in origin on Mars, Mercury, and Venus, are characterized by landforms referred to as wrinkle ridges (see Watters, 1988). Wrinkle ridges are long, segmented, anticlinal features with a complex morphology. They are composed of an assemblage of landforms that can be divided on the basis of morphology into two classes, broad arches up to 20 km wide and narrow ridges (first-, second-, and third-order) up to 6 km wide. Wrinkle ridges are believed to represent the surface expression of folding and thrust faulting (Plescia and Golombek, 1986; Watters, 1988). Anticlinal ridges in the flood basalts of the Yakima fold belt on the Columbia Plateau, northwestern United States, may be terrestrial analogues to wrinkle ridges. These structures have many of the same morphologic components that characterize planetary wrinkle ridges (Watters, 1988).

Whereas large-scale strike-slip faulting is a common mode of deformation on Earth, the lack of definitive evidence of lateral offset of craters and other landforms suggested that it was not common on the other terrestrial planets (Golombek, 1985). However, indirect evidence of strike-slip faulting has been found on Mars and Venus (Forsythe and Zimbelman, 1988; Schultz, 1989; Solomon et al., 1991). I examined direct and indirect evidence of strike-slip faulting associated with the folding and thrust faulting of the flood basalts of the Columbia Plateau and ridged plains material of Mars and Venus.

COLUMBIA PLATEAU, EARTH

The Columbia Plateau is a continental flood-basalt province located on the western margin of the North American plate. The Miocene basalts on the westernmost part of the plateau have been deformed into a series of long, narrow, regularly spaced anticlines with broad, flat, relatively undeformed synclines (Fig. 1, Table 1) (Price and Watkinson, 1989; Watters, 1988, 1989). As can be seen in Figure 1, numerous linear features occur in association with the anticlines and synclines of the fold belt. Right-lateral (mean strike N40°W) and left-lateral (mean strike N13°E) strike-slip faults have been documented in the southern part of the Yakima fold belt (Anderson, 1987). The horizontal displacement along the most extensive faults is typically small (<1 km). This amount of offset is insufficient to produce clear photographic evidence of offset of the anticlines that are typically 4–6 km wide.

A marked change in fold geometry across throughgoing strike-slip faults that form ridge-segment boundaries and evidence that some strike-slip faults have been folded indicate that strike-slip faulting and folding was contemporaneous, even though some strike-slip faults may predate the Columbia River Basalts (Anderson, 1987). Model experiments demonstrate that developing strike-slip faults can influence the geometry of simultaneously developing folds (Dubey, 1980). Conjugate pairs of strike-slip faults and thrust faults that appear to be contemporaneous have also been observed in Pennsylvanian-aged rocks in the Valley and Ridge province (Nickelsen, 1979). The growth of some of these strike-slip faults continued into a period of large-scale folding.

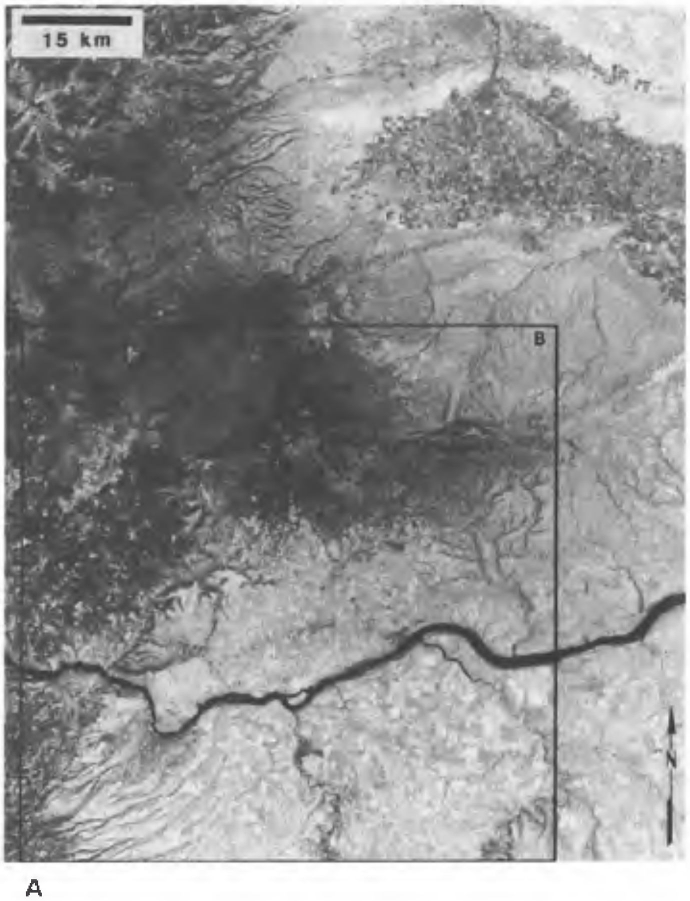
Landsat Thematic Mapper and Seasat Synthetic Aperture Radar images and topographic data have been used to study part of the Yakima fold belt for additional evidence of strike-slip faults in the form of prominent linear features. Many of the linear features identified correspond to previously mapped right-lateral strike-slip faults (Fig. 1; Table 2). The average orientations of the northwest-trending linear features agree with the average orientation of the right-lateral faults reported by Anderson (1987); however, linear features that correspond to the left-lateral set are less common in the images.

RIDGED PLAINS, MARS

The largest contiguous expanses of ridged plains material on Mars, in excess of 4×10^6 km^2 (~25 times the size of the Columbia Plateau), occur in the Tharsis province (comparable in surface area to South America) (Watters and Maxwell, 1986), a major center of volcanic and tectonic activity throughout the geologic history of Mars. Hundreds of wrinkle ridges occur in the ridged plains material and, like their counterparts on the Columbia Plateau, they are regularly spaced (Table 1) (Watters, 1991). Photographic evidence of lava-flow fronts and layering in the ridged plains material (e.g., Chapman and Tanaka, 1991) strongly suggests that these materials are flood volcanic in origin (see Watters, 1988).

Linear features, defined as discernible straight-line segments on the surface, are one of the few clues to the existence of strike-slip faulting on Mars. Convincing cases for strike-slip faulting on Mars have been made on the basis of indirect evidence of this kind. The Gordii Dorsum escarpment, about 1300 km west of the Tharsis Montes, has been interpreted as a left-lateral strike-slip fault zone, in part on the basis of the correspondence between the orientations of mapped arrays of linear topographic features and those associated with major strike-slip faults on Earth and in laboratory experiments (Forsythe and Zimbelman, 1988). Prominent linear features and plateaus in ridged plains material in the Coprates region, about 3500 km southeast of the Tharsis Montes, have been interpreted to be en echelon strike-slip faults and related push-up ranges (Schultz, 1989).

Linear features oblique to and associated with wrinkle ridges in the Tharsis province are not uncommon. Both en echelon and individual ridge segments often terminate sharply at linear features (typically <20 km long). These structures, observed in medium- and high-resolution



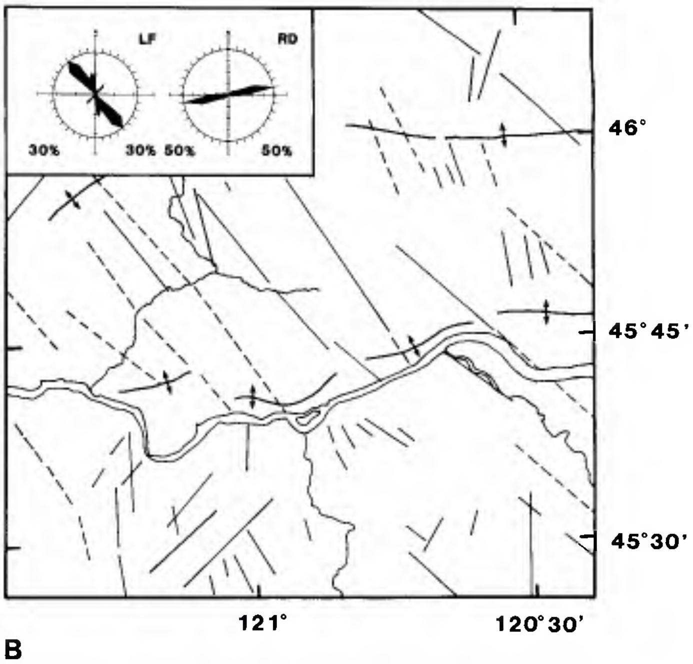


Figure 1. A: Landsat Thematic Mapper image of part of Yakima fold belt, Columbia Plateau. Long, narrow anticlinal ridges are separated by broad, relatively undeformed synclines. B: Map of area showing location of anticlinal ridges and known (dashed lines) and suspected (solid lines) strike-slip faults (area indicated in A). Linear features are shown as straight segments; anticlines are curvilinear segments with diverging arrows. Rose diagrams indicate distribution of orientations of prominent linear features (LF) (n = 65) and ridges (RD) (n = 57). Axes of diagrams represent percentage of total observations; tick marks around circles show center of 10° sampling bins.

TABLE 1. COMPARISON OF RIDGES IN PROVINCES STUDIED ON EARTH, MARS, AND VENUS

Location	Width (km)	Height (m)	Spacing (km)
Columbia Plateau, Earth	5*	300*	20†
Ridged Plains, Mars	3*	300*	30§
Lavinia Planitia, Venus	1	?	12

Note: Widths, heights and spacings are rounded mean values. Although the heights of the wrinkle ridges in the area study on Venus have not yet been estimated, the relief appears comparable to planetary wrinkle ridges.
*Watters (1988).
†Watters (1989).
§Watters (1991).

Viking Orbiter images, may be tear faults. Linear features with lengths <100 km that transect wrinkle ridges are rare. The best examples observed thus far are in southeast Coprates, near a contact between ridged plains and highlands material (Fig. 2, Table 2). Some of the linear features in this array can be traced into the adjacent highlands, and their exposure may be due to local erosion. Although the relative timing cannot be determined, that segments of the wrinkle ridges terminate at linear features suggests that these ridges were influenced by the presence of strike-slip faults (Fig. 2).

LOWLANDS, VENUS

Among the many tectonic features revealed in radar images of the surface of Venus from the Magellan spacecraft are landforms that are similar in morphology and dimension to wrinkle ridges (Solomon et al., 1991). Wrinkle ridges are remarkably common in the lowland plains of Lavinia Planitia, a broad lowland centered near 50°S, 340°W. The plains materials are almost certainly volcanic in origin (Head et al., 1991), and are possibly flood basalts. Wrinkle ridges in the plains material north of Hippolyta Linea (Fig. 3), a prominent groove belt, have an average width of about 1.0 km, placing them at the lower end of the range measured for first-order ridges on the Moon, Mars, Mercury, and Earth (Watters, 1988). Like their counterparts on Earth and Mars, wrinkle ridges in the plains material of Venus are regularly spaced (Table 1).

Wrinkle ridges on the plains north of Hippolyta are associated with cross-trending linear features. The most prominent of the linear features, orthogonal or nearly orthogonal to the northeast-trending wrinkle ridges, appear to be fractures or grabens (Fig. 3). Less obvious, but resolved in the Magellan images, are northeast- and northwest-oriented sets of cross-trending linear features ≤10 km long (Fig. 3, Table 2) that may be strike-slip faults. As on Mars, segments of some of the wrinkle ridges terminate at suspected strike-slip faults, suggesting that strike-slip faults influenced the development of ridges (see Fig. 3). Although strike-slip faults with large lateral offsets have not been observed, there is evidence of distributed shear in ridge and groove belts and mountain belts on Venus (Solomon et al., 1991).

DISCUSSION

The geometric relations between the wrinkle ridges and the strike-slip faults on Earth, Mars, and Venus can be explained in part by the Coulomb-Anderson model (Anderson, 1951). This model predicts fracture along two conjugate planes, bisected by the maximum and the minimum principal stresses, the intermediate principal stress being parallel to the line defined by the points of intersection of the two planes. If the maximum principal stress σ_{xx} is horizontal

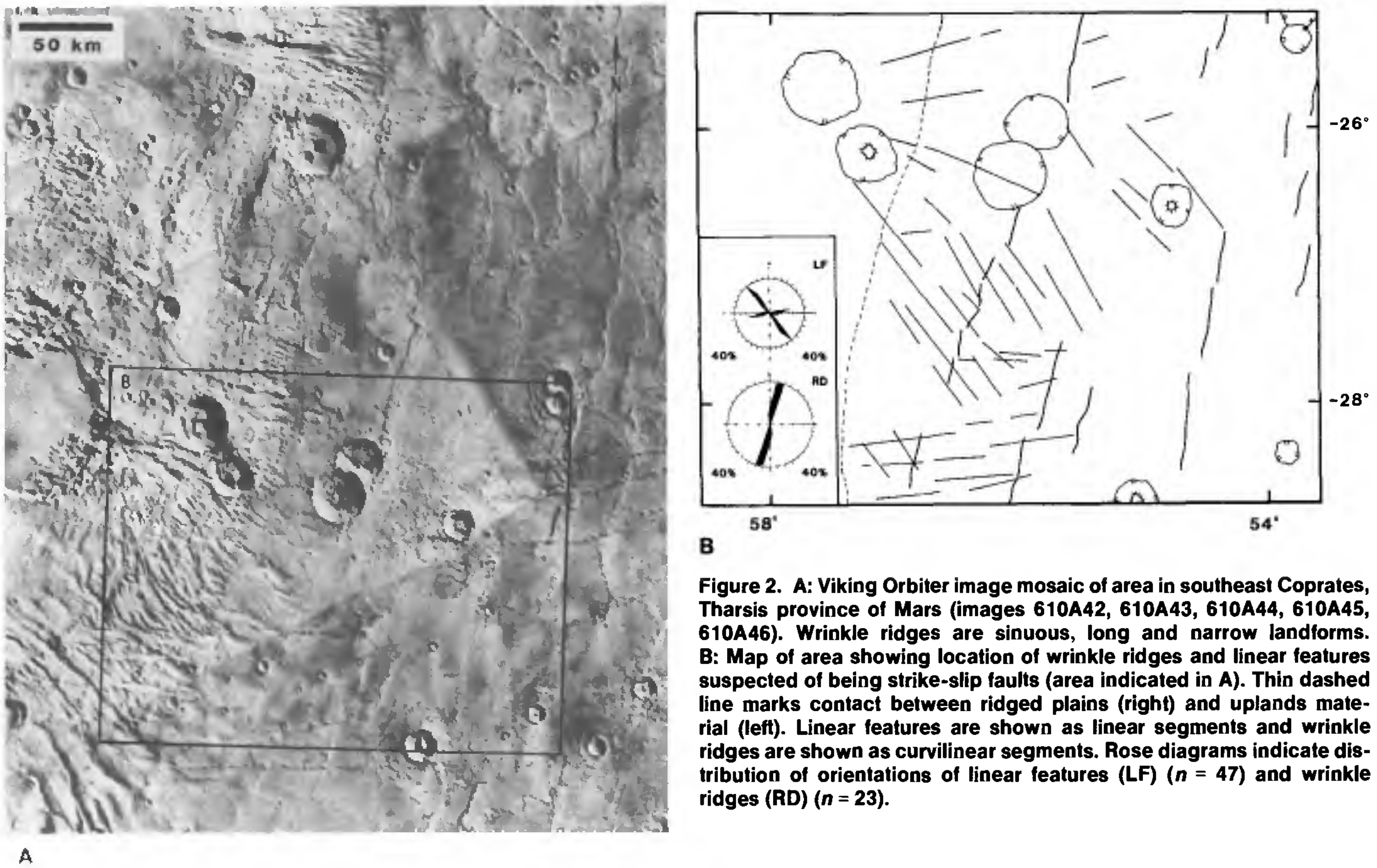


Figure 2. A: Viking Orbiter image mosaic of area in southeast Coprates, Tharsis province of Mars (images 610A42, 610A43, 610A44, 610A45, 610A46). Wrinkle ridges are sinuous, long and narrow landforms. B: Map of area showing location of wrinkle ridges and linear features suspected of being strike-slip faults (area indicated in A). Thin dashed line marks contact between ridged plains (right) and uplands material (left). Linear features are shown as linear segments and wrinkle ridges are shown as curvilinear segments. Rose diagrams indicate distribution of orientations of linear features (LF) (n = 47) and wrinkle ridges (RD) (n = 23).

and compressive, folds or thrust faults and conjugate sets of right-lateral and left-lateral strike-slip faults will form, respectively, perpendicular to and at an angle ±θ to the σ_{xx} direction (Fig. 4). Extension (i.e., normal faulting) requires the maximum stress to be vertical, the faults forming normal to the direction of minimum compression (σ_{yy}) or maximum tension. The optimum angle θ at which faulting will occur is given by

$$\theta = \tfrac{1}{2} \tan^{-1} (\mu^{-1}), \qquad (1)$$

where μ, by analog with ordinary sliding friction, is defined as the coefficient of internal friction (see Jaeger and Cook, 1979). Laboratory measurements of μ for a variety of rock types range from 0.6 to 0.9 (best fit $\mu = 0.85$) (Byerlee, 1978), corresponding to a θ of ~24° to 30°. This is in the range observed for the areas studied (Table 2). The uniform angular relation between the ridges and strike-slip faults in the areas studied suggests that the deformed materials on all three planets have similar frictional properties.

The Coulomb-Anderson model would not seem to permit simultaneous development of thrust faults and strike-slip faults because the direction of least compression must change from vertical to horizontal. Earthquake focal mechanisms determined for the Columbia Plateau and throughout the Pacific Northwest indicate, however, both thrust and strike-slip faulting (Crosson, 1972; Zoback and Zoback, 1980). One explanation is that the intermediate principal stress flips between vertical and horizontal as a result of changes in the stress field with time (see Nickelsen, 1979). Another possibility is inhomogeneity in the stress field. This could result from a more rapid increase of the vertical stress relative to the horizontal stresses with depth (Crosson, 1972). Under such conditions, thrust faulting would occur at shallow depths where the least compressive stress is vertical, and strike-slip faulting would begin at greater depths where the intermediate stress is vertical.

TABLE 2. AVERAGE ORIENTATIONS OF RIDGES AND KNOWN AND SUSPECTED STRIKE-SLIP FAULTS FOR PROVINCES STUDIED ON EARTH, MARS, AND VENUS

Location	Ridges	Faults		Inferred σ_{xx}		θ
		Set One	Set Two	⊥ to Ridges	Acute Bisector, Faults	
Columbia Plateau, Earth	N80°E	N40°W	N13°E*	N10°W	N14°W*	30°, 27°
Ridged Plains, Mars	N20°E	N40°W	N80°E	N70°W	N70°W	30°, 30°
Lavinia Planitia, Venus	N20°E	N80°E	N40°W	N70°W	N70°W	30°, 30°

Note: Values of θ are the difference between the inferred orientetions of σ_{xx} and the fault sets. The mode, evaluated using 10 sempling bins, is teken as the measure of the everage orientation of the structures. The more prominent fault set, defined by the number of observations, is designated fault set one.

*Data from Anderson (1987).

In the three areas studied, one set of strike-slip faults always appears to dominate. The Coulomb-Anderson model predicts two equally important conjugate planes of failure. The development of a dominant plane of failure may be an effect of anisotropy on shear failure (Jaeger and Cook, 1979).

CONCLUSIONS

The deformation of broad expanses of volcanic plains on Mars and Venus and the flood basalts of the Columbia Plateau resulted in a system of tectonic features consisting of regularly spaced folds and/or thrust faults (wrinkle ridges) and conjugate sets of cross-trending strike-slip faults. The wrinkle ridges and strike-slip faults in these regions of distributed deformation reflect a relatively small amount of

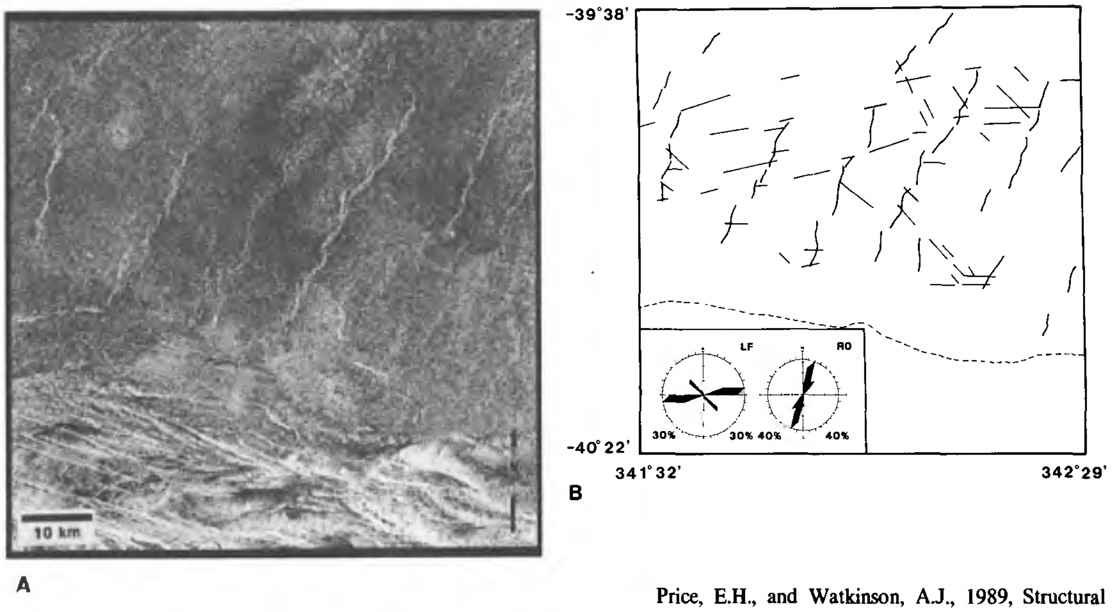


Figure 3. A: Magellan radar image of ridged plains of Lavinia Planitia, north of Hippolyta Linea, Venus (F-MIDRC.40S342.FF28). Landforms analogous to wrinkle ridges dominate lowland plains. B: Map showing location of wrinkle ridges and linear features suspected of being strike-slip faults. Thin dashed line marks contact between ridged plains (top) and Hippolyta Linea groove belt (bottom). Rose diagrams indicate distribution of orientations of linear features (LF) (n = 51) and prominent wrinkle ridges (RD) (n = 28).

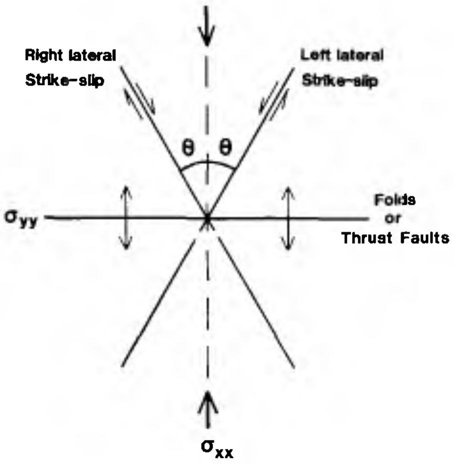


Figure 4. Geometric relations between structures predicted by Coulomb-Anderson model. Angle θ between strike-slip faults and maximum compressive stress direction σ_{xx} is directly related to coefficient of internal friction of material (see equation 1 in text).

crustal shortening. Strike-slip faults appear to have influenced simultaneously developing wrinkle ridges. The Coulomb-Anderson model can account for the geometric relations between the structures for realistic values of the coefficient of internal friction.

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