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Wrap-Around Dune

► Climbing Dune

Wrench Fault

► Strike-Slip Faults

Wrinkle Ridge

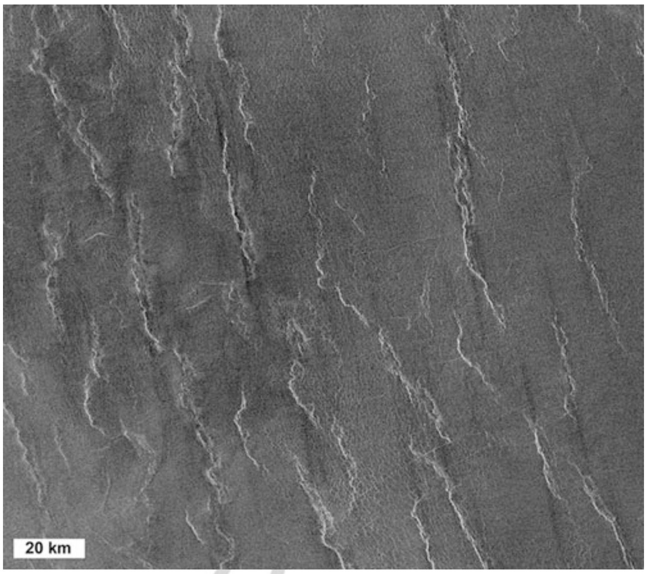
Jarmo Korteniemi[1,2], Lisa S. Walsh[3] and Scott S. Hughes[4]
[1]Earth and Space Physics, Department of Physics, University of Oulu, Oulu, Finland
[2]Arctic Planetary Science Institute, Rovaniemi, Finland
[3]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC, USA
[4]Department of Geosciences, Idaho State University, Pocatello, ID, USA

Definition

Asymmetrical ridge, typically composed of a broad linear rise and complex crenulations, which occur on a broad, low-relief arch (Watters 1988; Schultz 2000).

Synonyms

Descriptive: ridge, mare ridge, wrinkled mare ridge, mare ridge-highland scarp system (Lucchitta 1976). Interpretative: contractional lineament, Bergader ('mountain vein', german, Schröter 1791), pressure ridge



Wrinkle Ridge, Fig. 1 Venus: subparallel wrinkle ridges, some displaying smaller-scale lineation, in Aditi Dorsa near 31°S 194°E. Magellan left-look radar (NASA/JPL)

Description

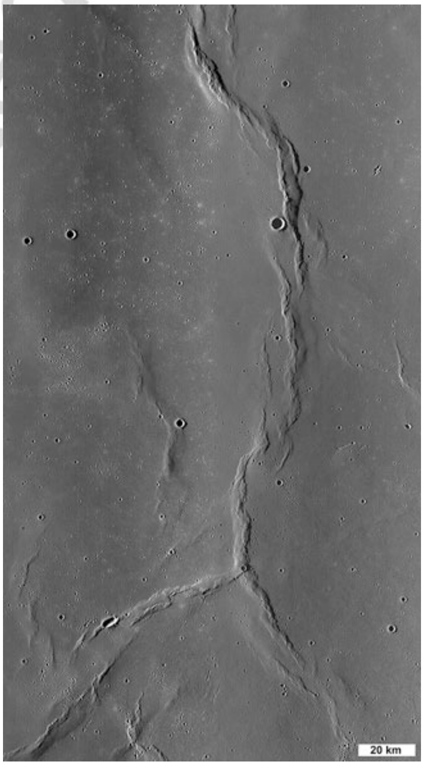
Linear arc-shaped or sinuous topographic highs, preferentially found on lowland/plains areas (Golombek et al. 2001), occurring in quasi-regular or periodic spacing (Watters 1991) often in en echelon overlapping sets. They are often bifurcating or anastomosing (Lucchitta and Klockenbrink 1979), braid, and rejoin along strike (Plescia and Golombek 1986). They have asymmetrical profiles (one side having a steeper slope than the other).

Morphometry

Wrinkle ridges are 10s–100s of m high (highest on Mercury), up to 100s of km long, and few to 10s of km wide, displaying 10s of km spacing.

Mercury (in the northern smooth plains and in and around Caloris Basin): Wrinkle ridges are ~112–961 m high (mean = 187 m) and ~10–241 km long (mean = 53 km) (Walsh et al. 2013).

Venus (Fig. 1): Wrinkle ridges are 1–5 km wide, 100s of m high, and 100s of km long. They often form large-scale parallel sets with interridge spacing of few tens of km. These wrinkle ridge sets extend for 1,000s of km (Bilotti and



Wrinkle Ridge, Fig. 2 Serpentine Ridge (Dorsa Smirnov) in Mare Serenitatis on the Moon, concentric to the mare basin, centered 28°N 30°E. LROC M117338863M and M117318506M (NASA/GSFC/ASU)

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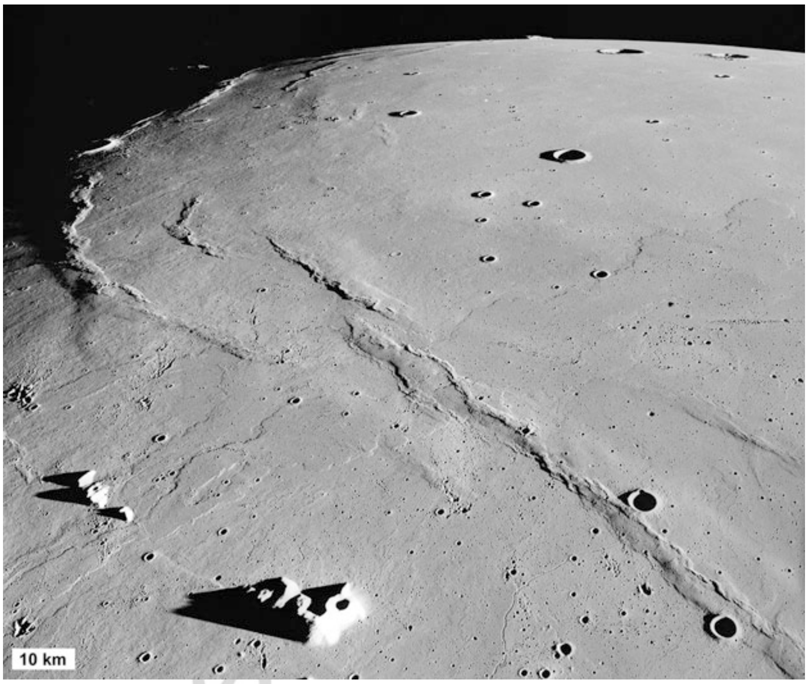
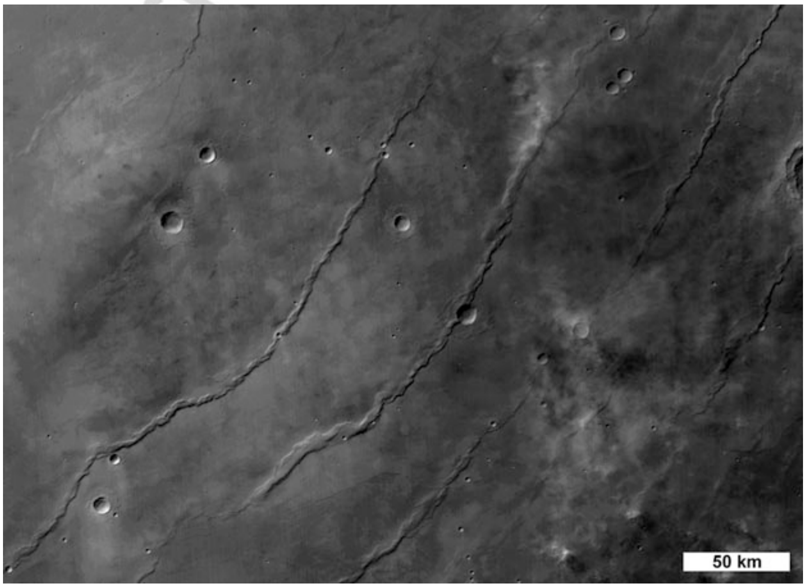
Suppe 1999). On Venus, they are systematically narrower and have shorter spacing than on other terrestrial planets (Kreslavsky and Basilevsky 1998).

Moon (in mare basins and several craters) (Figs. 2 and 3): Wrinkle ridges are ~33–590 m high (mean = 187 m) and ~10–241 km long (mean = 53 km) (Walsh et al. 2013).

Mars (Figs. 4 and 5): Wrinkle ridges are 10–20 km wide, 10s–100s of km long, and 80–250m high (in Solis Dorsa, Fig. 4), showing elevation offsets of the plains on either sides of



Wrinkle Ridge, Fig. 3 Moon: perspective view of wrinkle ridges near Mons La Hire, in Mare Imbrium. AS15-M-1555 (NASA/JPL/ASU)



Wrinkle Ridge, Fig. 4 Solis Dorsa: subparallel wrinkle ridges in Solis Planum, Mars. MOC mosaic (NASA/JPL/MSSS)

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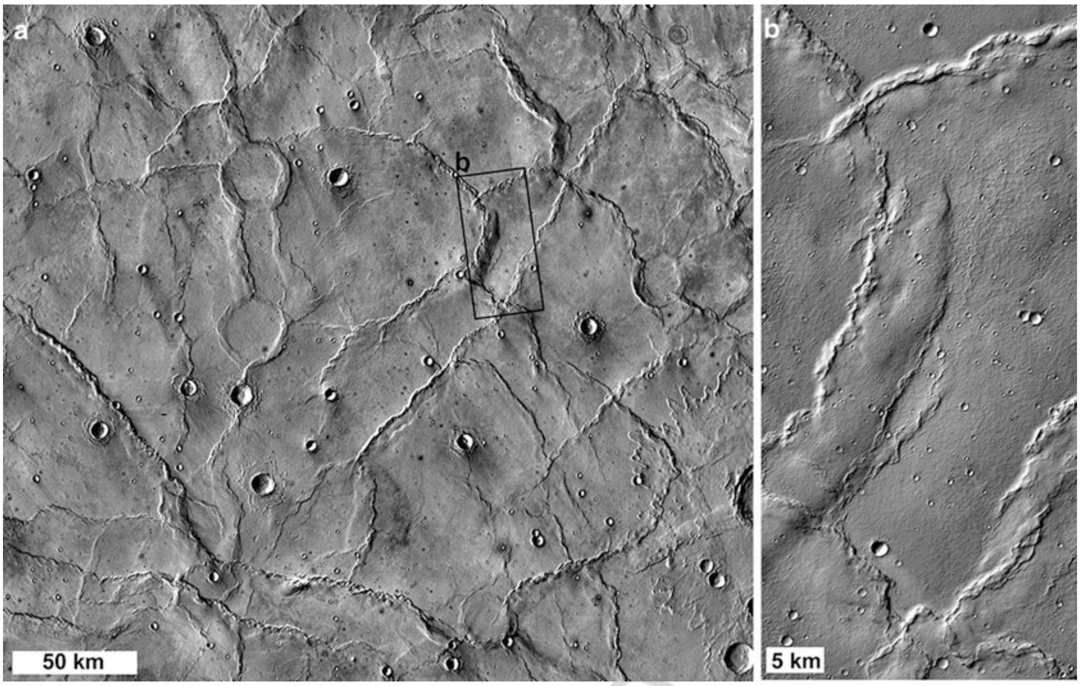


Wrinkle Ridge, Fig. 5 The Hesperia Dorsa wrinkle ridges that show bimodal trending in Hesperia Planum, Mars, (**a**) THEMIS IR mosaic centered 20°S 113°E (NASA/JLP/ASU), (**b**) CTX: B01_010152_1606_XN_19S245W (NASA/JPL/MSSS)

wrinkle ridges ranging 50–180 m (Golombek et al. 2001). Tharsis wrinkle ridges have an average spacing of 30–50 km (Watters 1991; Head et al. 2002).

Subtypes

Based on orientation (Bilotti and Suppe 1999; Head et al. 2002):

(1) Unimodal/subparallel (Figs. 1 and 4)
(2) Bimodal (with two equal trends or a major and a minor trend) (Fig. 5)
  (2.1) Orthogonal
  (2.2) Oblique
(3) Polygonal (parallel trends interrupted by variable angular orientations)
(4) Random
(5) Ring (▶ wrinkle ridge rings)

Formation

Wrinkle ridges are contractional tectonic features formed by a combination of folding and thrust faulting. They form in response to uniformly distributed compressional stresses in the upper layers of the surface where a strong brittle layer overlies a weaker layer (e.g., lava overlying megaregolith or layering present in lava flows). They accommodate very low amounts of shortening strain (Mueller and Golombek 2004).

Their formation is not consistent with a medium where a weak layer overlies another weak layer (e.g., sediment overlying megaregolith) (Head et al. 2002; Mueller and Golombek 2004).

Compressional stresses may be induced by lithospheric loading of volcanic plains (e.g., mare basalts (Watters 1993)), sediments, lahar-like deposits, water, or ice (Thomson and Head 2001).

Formation Models

(1) Simple thrust fault in rigid crustal blocks (Schultz 2000 and references therein).
(2) Conjugate thrust fault (pop-up model): a wrinkle ridge is a wedge bounded by two conjugate thrust faults (Schultz 2000 and references therein).
(3) Thrust faults and backthrust fault: thrust faulting causes the main ridge, whereas wrinkles are interpreted as backthrust faults (Schultz 2000).
(4) Low-amplitude compressive anticlines above subsurface blind thrust faults: anticlinal folding of rocks occurs over a buried (blind) thrust fault. Wrinkle ridges form as the subjacent fault propagates upward (Plescia and Golombek 1986; Bilotti and Suppe 1999 and references therein, Golombek et al. 2001).
(5) Low-amplitude buckle fold: "folds, resulting from buckling followed by reverse to thrust faulting (flexure-fracture)." In this model, wrinkle ridges are shallow near surface structures (Watters 1991 and references therein, Schultz 2000 and references therein).

Possible Sources of Compressive Stresses

These include (1) thermal subsidence following plume-related thermal topographic uplift, (2) subsidence in response to volcanic surface loading by flood basalts, (3) subsidence due to deep crustal loading by dense underplated magmas (Mège and Ernst 2001), and (4) global contraction due to interior cooling. Global contraction may have a more substantial contribution to wrinkle ridge formation on *Mercury* than on the *Moon* (Walsh et al. 2013; Byrne et al. 2014). On *Venus*, wrinkle ridges are estimated to represent little (~2–5 %) regional shortening of the terrain (Bilotti and Suppe 1999). Global distribution on *Mars* is proposed to be associated with a hypothesized global contraction (Nahm and Schultz 2011).

Controls

On *Mercury*, they are longer and higher than on the Moon, which may be due to differences in thickness of plains material that controls the maximum depth of faulting, contribution of subsidence, and amount of global contraction (Walsh et al. 2013).

Age

Interaction of wrinkle ridges with craters on Mars (Allemand and Thomas 1995; Mangold et al. 1998; Head et al. 2002) indicates that wrinkle ridges formed significantly later than the plain units they deform. However, their formation has apparently ceased long ago.

Surface Units

Wrinkle ridges may display one, or several of the following (Strom 1972; Lucchitta 1976; Fig. 3):

(1) Broad arch: a broad, low-relief arch on which wrinkle ridges develop. "A linear to convex slope that rises from a flat or slightly tilted surface toward the center of the ridge" (Mueller and Golombek 2004). Most authors make this arch a part of a wrinkle ridge structure, but Schultz (2000) notes that they may or may not be genetically related to wrinkle ridges and they may be only spatially associated. On Mars, Solis Planum, they are about 50 m high and 30–50 km wide (Mueller and Golombek 2004).
(2) Ridge: broad, linear rise, or ridge or hill. It is generally narrower and steeper than the broad arch (Mueller and Golombek 2004).
(3) Wrinkle: sinuous, complex, narrow, low-relief, discontinuous, or en echelon crenulations (the wrinkles) typically near a ridge's margin, sometimes on its top or in the surrounding terrain (Schultz 2000).

Composition

They are consistently located in stratified volcanic and sedimentary deposits (Mueller and Golombek 2004). Based on stratigraphic relations, wrinkle ridges may deform the following material units:

(1) Volcanic plains.
(2) Sedimentary plains.
    (2.1) Mantled wrinkle ridge (Thomson and Head 2001) deposition of sediment was subsequent to wrinkle ridge formation.
    (2.2) Wrinkle ridge formed in the sedimentary layer.
(3) Impact ejecta plains.

Prominent Examples

On *Venus*, Aditi Dorsa (Fig. 1); on the *Moon*, Dorsa Smirnov and Dorsa Lister (Serpentine Ridge) wrinkle ridge system in Mare Serenitatis (Fig. 2).

Distribution

Wrinkle ridges occur on topographically smooth material on the Moon, Mercury, Mars, and Venus in two physiographic settings: the interior of large impact basins (e.g., Mare Serenitatis on the Moon or the Caloris Basin on Mercury) and on broad expansive plains (e.g., the northern plains of Mercury) (Watters 1988; Watters and Johnston 2010; Watters and Nimmo 2010).

On Mercury, they occur in the smooth plains and the Caloris Basin interior and exterior (knobby/hummocky) plains (Plescia and Golombek 1986 and references therein, Watters et al. 2009; Walsh et al. 2013).

On Venus, they mostly occur in the ► wrinkle ridge (regional) plains unit. Majority of plains with wrinkle ridges lie below the mean planetary radius (in geoid lows). Aditi Dorsa shows the highest density of wrinkle ridges (Bilotti and Suppe 1999).

On the Moon, wrinkle ridges are found in the mare basins (Masursky et al. 1978; Plescia and Golombek 1986) (see figure in ► linear rille) and in craters (e.g., Vitello, Kugler, Karrer, and Grimaldi) (Walsh et al. 2013).

On Mars, they are distributed globally (Chicarro et al. 1985; Nahm and Schultz 2011) and mostly occur in the Hesperian ► Wrinkle ridge plains (Head et al. 2002). Wrinkle ridges show a circumferential trend around Tharsis (e.g., Nahm and Schultz 2011). Martian wrinkle ridges are up to 400–600 km long, and yet they seem to accommodate very low local strains (about 100s of m of shortening across individual ridges) (Mueller and Golombek 2004).

Significance

They are the result of horizontal shortening of the surface strata (Schultz 2000). Wrinkle ridges are generally thought to indicate volcanic layers, partly because volcanic features are of greater abundance on planetary surfaces. However, wrinkle ridges per se are only indicative of a stack of subsurface layers or vertical inhomogeneity in the material (Gregg and de Silva 2009 and references therein).

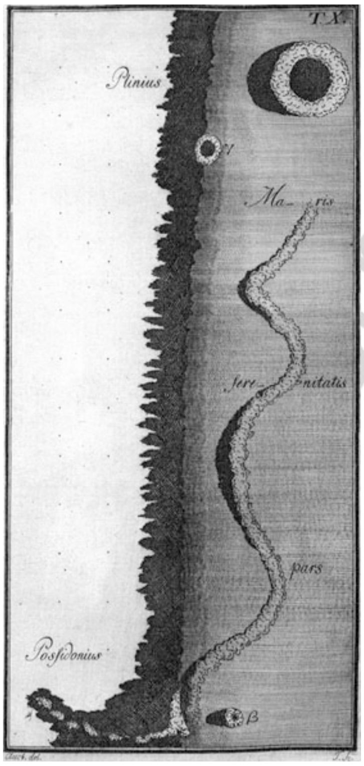
Terrestrial Analog

The best analogs are found in the anticlinal ridges of the Yakima fold and thrust belt of the Columbia River Plateau in the Pacific Northwest, interpreted as layered basalt flows draped over thrust faults (Lucchitta and Klockenbrink 1979; Plescia and Golombek 1986; Watters 1988); small foreland basement uplifts (e.g., Oregon Basin thrust, Wyoming, USA) (Golombek et al. 2001) produced by anticlinal folding of rocks above reverse faults that become shallow and typically break the surface (Plescia and Golombek 1986). Some of the terrestrial analogs formed in a layered sedimentary material (e.g., Meckering, Australia; El Asnam, Algeria) (Plescia and Golombek 1986).

History of Investigation

Originally found to exist on lunar maria by telescopic observations, wrinkle ridges were named Bergader (German, mountain + vein) by Schröter (1791:§335, 356); he described other similar types as "light veins" (Lichtadern) or gray veins that were only visible near the terminator. Schröter first observed and described the "snake-like" wrinkle ridge (Fig. 6) later called Great Serpentine Ridge in English (Elger 1895) (today: Dorsa Smirnov). Beer and Mädler (1837:126§70) also noted that these low ridges can be seen only near the terminator.

J. Phillips "compared the lunar ridges to long, low, undulating mounds, of somewhat doubtful origin, called 'kames' in Scotland, and 'eskers' in Ireland," while others suggested that they "represent old submarine banks formed by tidal currents, like harbour bars, or glacial deposits; in either case, to be either directly or indirectly due to alluvial action" (Elger 1895).



Wrinkle Ridge, Fig. 6 First depiction of the Serpentine Ridge on the Moon (see Fig. 2) (Table 10 from Schröter 1791) (e-rara.ch)

Kuiper (1954) suggested that wrinkle ridges result from compression due to downward-moving differential cooling of the crust: when "cooling in the outer shell had largely run its course, and gradually deeper and deeper layers followed. This caused the deeper layers to shrink in turn; but now the outer layers, in which the cracks had meanwhile been largely filled by new lavas, began to be compressed, since their temperatures were nearly constant but their base narrowed. Folding would therefore result. In this manner the ridges, visible particularly on the maria, may be explained" (Kuiper 1954).

Most models in the 1960s focused on volcanic intrusion or extrusion, controlled by global or basin-related tectonic patterns (Lucchitta 1976 and references therein).

In the 1970s, an alternative model to explain thrust faulting was the model of regional cooling of volcanic plains, which was subsequently rejected (Mangold et al. 2000).

Schultz (2000) called wrinkle ridges "probably one of the most commonly observed, yet least understood, classes of planetary structures."

Database

Bilotti and Suppe (1999) mapped over 65,000 wrinkle ridges on Venus.

IAU Descriptor Term

► Dorsum, dorsa (e.g., in lunar maria).

Similar Landforms

► High-relief ridge; ► lobate scarps: smaller than wrinkle ridges and usually found in the highlands but also in mare materials and in transition to wrinkle ridges (Lucchitta and Klockenbrink 1979; Watters 1993; Head et al. 2002; Watters et al. 2010).

See Also

- ► Reverse Fault
- ► Wrinkle Ridge Plains
- ► Wrinkle Ridge Ring

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Wrinkle Ridge Plains

Scott S. Hughes
Department of Geosciences, Idaho State University, Pocatello, ID, USA

Definition

Plain that has developed topographically distinct sinuous or nearly linear ridges on an otherwise relatively smooth surface.

Category

A type of ► volcanic plain.

Synonyms

Dorsum plains; Plains with wrinkle ridges (Moon, Venus); Regional plains (Venus); Ridged plains (Mars); Wrinkle ridged plains (Mars)

Description

Wrinkle ridge plains (e.g., Watters 1991) are characterized by two principle topographic features: broad ridges up to tens of kilometers wide and sinuous and discontinuous (or en echelon) crenulations on or near ridges (Schultz 2000).

Morphometry

► Wrinkle ridge

Interpretation

Contractional tectonic features on volcanic or sedimentary plains (e.g., Watters 1993). On the Moon, formed by contraction related to subsidence of lava flow sequences in lunar maria (basins); on the high volcanic plains of Mars, Venus, and Mercury, related more to internal tectonic forces caused either by gravitational loading of large volcanic constructs or by coupled mantle-crust dynamics including mantle plumes. The relatively linear ridges on the wrinkle ridge plains of Mars have distinct elevation offsets and are interpreted to represent subsurface thrust faults (Golombek et al. 2001). Mège and Ernst (2001) interpret wrinkle ridges on Earth, Mars, and Venus as contractional structures (thrust-faulted anticlines) related to mantle plumes.

Formation

After emplacement, plains material is subsequently deformed by compressional/contractional forces producing ► wrinkle ridges (Basilevsky and Head 1996). Wrinkle ridge plains on lunar mare basins, developed by thin-skinned buckling during cooling, contraction, and subsidence of basin interiors, are likely caused by loading of multiple layers of lava (several kilometers thick in basin interiors) that resulted in compressional tectonic forces and shortening of surface layers. The wrinkle ridge plains on high-elevation plains of Mars are developed by thick-skinned compressional tectonic forces in the lithosphere leading to deep-seated thrust faults (Golombek et al. 2001; Montési and Zuber 2003), whereas wrinkle ridge plains (regional plains) on Venus are interpreted to reflect tectonic deformation related to mantle convection motions coupled to a more rigid crust (Squyres et al. 1992).

Age

On Venus, wrinkle ridges are abundant on volcanic plains that represent an extensive episode of