Wrinkle ridges as indicators of volcanic deposits

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Abstract. Wrinkle ridges on the terrestrial planets have been used as evidence of a basaltic material in which they occur. There is evidence to support both volcanic and tectonic origins of wrinkle ridges. Most terrestrial analogs indicate that wrinkle ridges are the result of a tectonic process in a layered medium. The presence of wrinkle ridges should only be used as supplemental evidence of a volcanic substrate, not an indicator.

1. Introduction

Mare-type wrinkle ridges have been identified on the Moon, Mars, Mercury and Venus. Mare-type wrinkle ridges are linear to arcuate asymmetric topographic highs, which consist of a broad arch topped by a crenulated ridge (Figure 1) (Strom, 1972; Watters, 1988). Wrinkle ridges are morphologically complex, commonly consisting of superimposed landforms (Watters, 1988). The presence of wrinkle ridges on, for example, Martian plains material has been used to infer a volcanic origin (e.g., Carr, 1973), mainly because on the Moon wrinkle ridges are found exclusively in the mare basalt units (Quaide, 1965). Many mechanisms have been suggested to explain their origin; volcanic intrusion and/or extrusion (e.g., Baldwin, 1963; Ronca, 1965; Howard and Muehlberger, 1973), tectonic (e.g., Watters, 1988; Golombek et al., 1991) and combinations of these processes (e.g, Colton et al., 1972). Recent studies generally agree that wrinkle ridges are the result of tectonic compression (e.g., Watters, 1988; Golombek et al., 1991; Schultz, 2000). This paper is a review of the evidence to support a volcanic model for the genesis of ridged plains units, and evidence that the presence of wrinkle ridges may not be a good indicator of a volcanic deposit. The final section of this paper is a procedure for constructing wrinkle ridges that show morphological variability using a layered material.

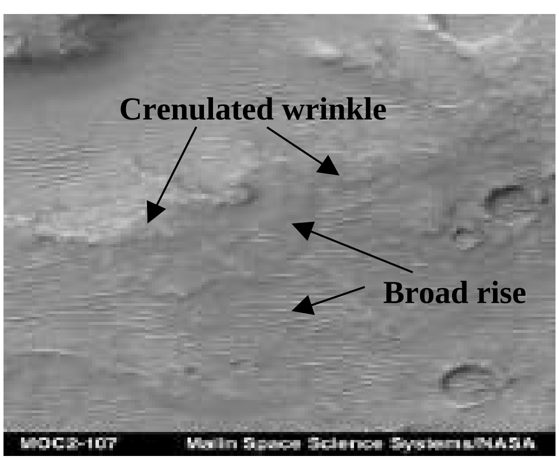

Figure 1. Wrinkle-ridge in northern Hesperia Planum, Mars showing crenulated "wrinkle" portion of the ridge and the associated broad rise.

2. Evidence of a Volcanic Source

2.1. Moon

On the Moon, wrinkle ridges occur on almost all mare surfaces, which are dark areas covered with basaltic lava, and are commonly concentric with margins of circular maria (Fielder, 1961). The flow-like appearance of mare ridges and the style by which ridges modify preexisting impact craters is the most compelling evidence of the hypothesis that mare ridges are volcanic landforms (Figure 2) (Table 1) (Sharpton and Head, 1988). It should be noted that most of the work on the origin of wrinkle ridges has been done on lunar examples, where a variety of imaging and altimetric data sets have been used to constrain their formation (e.g., Sharpton and Head 1982, 1988). Other evidence for a volcanic origin is listed in Table 1 and includes: the sinuous appearance and patterns of surface features, and the interpretation of the broad rise as a laccolith (Quaide, 1965; Strom, 1972; Scott, 1973).

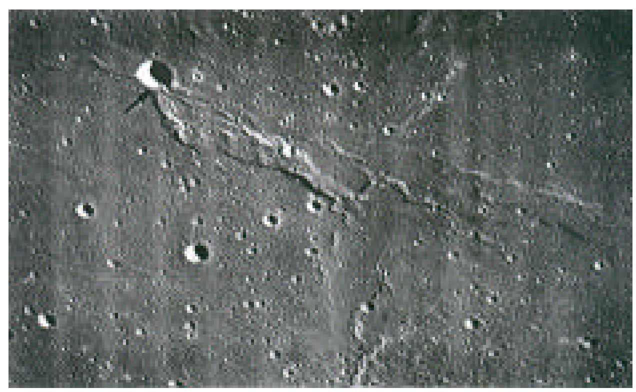

Figure 2. Lunar wrinkle-ridge showing a small crater (approximately 1 km diameter) that has been modified by a narrow, welt-like mare ridge lobe extending into the crater interior. (From Sharpton and Head, 1988; Apollo 16-119-19158).

Table 1. Evidence cited for the origin of mare-type wrinkle ridges as being from a volcanic source

Location	Evidence
Moon	Modification of impact craters by flow-like pattern of wrinkle ridge
Moon	Found in lunar maria, which is known to be basalt
Moon	Positive gravity anomaly associated with some ridges may suggest dike intrusion

Moon	Ropy, braided, overlapping or discontinuous pattern, which suggests extrusion
Mars	Found in volcanic calderas of shield volcanoes
Mars, Venus, Moon, Mercury	Broad arch suggests laccolith
Mars, Venus, Moon, Mercury (?)	Ridged plains are associated with volcanic centers.
Venus	Occur in lowlands of Venus, which are likely to be basaltic

Taken from Strom 1972; Bryan, 1973; Hodges, 1973; Howard and Muehlberger, 1973; Scott, 1973; Young et al., 1973; Colton et al., 1972; Lucchitta, 1976, 1977; De Hon and Waskom, 1978; El-Baz, 1978; Fagin et al., 1978; Maxwell et al., 1978; Scott et al., 1978; Solomon and Head, 1979; Sharpton and Head, 1982, 1988; Watters, 1988; Solomon et al., 1991.

2.2. Mars, Venus, and Mercury

Interpretations of a volcanic origin for wrinkle-ridges on Mars are made largely by strong morphologic similarity to mare ridges. These assemblages occur in a variety of settings: (1) the Tharsis Plateau (e.g., Lunae Planum, Solis Planum, Syria Planum, Sinai Planum); (2) the Amazonis and Chryse lowlands, (3) the plains of Syrtis Major, Hesperia Planum, and Malea Planum, (4) in basins (e.g., Schiaparelli), (5) intercrater plains (e.g., Phaethontis), and (6) within the Ascraeus Mons and Olympus Mons calderas (Greeley and Spudis, 1981; Watters, 1988). Ridged plains are associated with volcanic centers, and large basins resemble mare basins, which supports the interpretation that wrinkle ridges are the result of a volcanic process (e.g., Scott and Carr, 1978; Maxwell and Gifford, 1981; Greeley and Spudis, 1981; Watters, 1988).

Wrinkle ridges on Mercury occur in smooth plains, hummocky plains, and intercrater plains, but most occur in the smooth plains material (Strom et al., 1975). The smooth plains material has been interpreted as the result of flood volcanism, in part due to the presence of wrinkle ridges and their analogy with the lunar and martian wrinkle ridges (Strom et al., 1975). The presence of a magnetic field indicating that Mercury may have a partially molten metallic core supports arguments for volcanism on the planet (BVSP, 1981). However, an unequivocal case for a volcanic origin cannot be made due to lack of photogeologic evidence of volcanic landforms (Wilhelms, 1976).

The Magellan spacecraft radar images revealed landforms that are similar in morphology and dimension to wrinkle ridges (Solomon et al., 1991). These are common in the lowland plains, which are almost certainly of a volcanic origin, possibly flood basalts (Head et al, 1991; Solomon et al., 1991).

2. Evidence of a Tectonic Source

The most compelling evidence of a tectonic origin for planetary wrinkle ridges comes from the Apollo Lunar Sounder Experiment (ALSE) data (Peeples et al., 1978; Maxwell and Phillips, 1978). ALSE data indicate that slopes on the flanks of most lunar ridges are only a few (1^o to 6^o) degrees, and the sense of asymmetry can reverse along the length of the ridge, alternating from one side to the other (Maxwell et al, 1975; Plescia and Golombek, 1986). ALSE data also show evidence of thinning of a mare unit (sequence of flows on apparent structural relief (Maxwell et al., 1975). A tectonic origin is supported by a variety of data including stratigraphic relationships, relative ages, and cross-sectional analyses (Table 2).

Table 2 lists evidence that supports mare-type wrinkle ridges having tectonic deformational mechanism. Evidence to support a tectonic origin for wrinkle ridges on Mercury and Venus is based on analogy to the Moon, Mars, and Earth. Terrestrial analogs will be discussed in the following section.

Table 2. Evidence cited for the origin of mare-type wrinkle ridges as being from a tectonic source

Location	Evidence
Moon, Mars, Venus, Mercury	Surface topography implies tectonic deformation
Moon, Mars, Venus, Mercury	Several ridges extend into the highlands as fault scarps
Moon, Mars, Venus, Mercury	Vertical offsets occur across some ridges
Moon, Mars	Ridges modify some fresh craters, implying the latest ridge formation postdates last regional volcanic episodes
Moon, Mars, Venus, Mercury	May occur in en echelon arrays
Moon	Some ridges cross volcanic boundaries
Moon	Wrinkle ridges often occur over premare topography
Moon	Deformation of postmare craters by shortening as a result of wrinkle ridges
Moon	Some locations correlate with changes in basalt thickness where stresses might be localized
Moon	Regional trends are consistent with global fracture patterns
Moon	Circular basing trends are consistent with deformation due to loading by mare fill
Moon	Local ridge trends may parallel regional topographic contours
Mars	Wrinkle ridges cross-cut each other in a consistent manner, implying two deformational episodes (e.g., Hesperia Planum)
Mars	Wrinkle-ridge deflection around buried impact craters suggests deformation postdates crater burial

Mars	Appear in some areas where there is no evidence of lava flow features
Mars	May be concentrated very large distances away from volcanic vents

Taken from: Bryan, 1973; Young et al., 1973; Colton et al., 1972; Lucchitta, 1976; El-Baz, 1978; Raitala, 1978; Scott et al., 1978; Solomon and Head, 1979; Greeley and Spudis, 1981; Plescia and Golombek, 1986; Golombek et al. 1991; Maxwell et al., 1975; Sharpton and Head, 1982, 1988; Watters, 1988

3. Terrestrial Analogs

The most recognized terrestrial analogs to planetary wrinkle ridges include formation by a tectonic process, however it must be noted that most favored occur in volcanic media. Hodges (1973) believes that wrinkle ridges are analogous to features formed in Alae crater, Hawaii during the Mauna Ulu eruptions. Alae crater was a lava lake that developed a surface crust that underwent compressional sagging when the lava drained out of it, causing pieces of solidified crust to override one another. This type of deformation may be similar to the formational mechanism of wrinkle ridges in the calderas on Mars (Plescia and Golombek, 1986).

Morphologically and dimensionally, the Yakima member of the Columbia Plateau is the most common terrestrial analog to planetary wrinkle ridges (e.g., Plescia and Golombek, 1986; Watters, 1988, 1991). The Yakima ridges are interpreted to be layered basalt flows draped over thrust faults (Bentley, 1977). Other terrestrial analogs include: thrust faults in Meckering, Australia; El Asnam, Algeria; and Buena Vista Hills, California. All of these terrestrial analogs contain a thrust fault in sandy lateritic soil, sedimentary rock, and layered sand-clay-shale, respectively, and are associated with an anticlinal fold (Plescia and Golombek, 1986).

4. Discussion

Despite the evidence cited here there are several problems that remain unresolved. Some lunar wrinkle ridges are most likely the result of a volcanic process, but this does not appear to be the case for all wrinkle ridges (Wilhelms, 1987; Maxwell, 1989). Tectonic implications of planetary wrinkle ridges with an enigmatic source both regionally and locally remain uncertain. Global contraction and despinning may explain those on the Moon and Mercury, but not the genesis of many Martian wrinkle ridges, especially those occurring in the ridged plains material (Melosh, 1978; Solomon and Head, 1979; Solomon and Head, 1980; Greeley and Spudis, 1981; Watters, 1988).

The surface morphology of Martian wrinkle ridges probably results from multi-layer subsurface strata deformed by a tectonic process (Watters, 1991; Schultz, 2000). The mare basalts are brittle, competent, and layered, whereas the highland material is brecciated, therefore, the presence of mare-type wrinkle ridges on planetary bodies can be used to infer the presence of competent, brittle rocks (Greeley and Spudis, 1981).

5. Summary

Wrinkle-ridges on planetary bodies have been thought to be indicative of a volcanic substrate in which they occur. The presence of wrinkle ridges is controversial evidence for a volcanic media, because it is found in areas where there is no evidence of volcanic flows, flow features, or vents. Most likely wrinkle ridges are the result of a folded, faulted layered material that possesses similar qualities to basalt. As seen in some terrestrial analogs, wrinkle-ridge-type structures may be formed in a layered sedimentary material. Therefore, the presence or absence of ridges should only be used as supplemental evidence for a basaltic composition of the media in which they are found.

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