

MORPHOLOGY AND SUBSURFACE STRUCTURE OF WRINKLE RIDGES ON MARS. M.E Cryder¹ and J. C. Andrews-Hanna², ¹Lunar and Planetary Laboratory, University of Arizona (mecryder@email.arizona.edu).

Introduction: Wrinkle ridges are compressional tectonic features that are produced through a combination of folding and faulting in the subsurface [1]. These features exhibit variability in ridge height, length, and morphology. On Mars, wrinkle ridges are common throughout the volcanic surfaces, particularly within the tectonically active region of Tharsis. They are observed to be tens to hundreds of kilometers long, with typical widths of ten kilometers [2].

There are at least four distinct morphological types of ridges: symmetric, asymmetric ramp, arch, and double ridges [3] with arches being less common. Many wrinkle ridges also demonstrate an offset between the elevation of the surrounding surface beyond the forelimb and backlimb, interpreted as evidence for a lithosphere-scale thrust fault [2]. Alternatively, other researchers interpret wrinkle ridges as thin-skinned structures confined to the volcanic plains [1]. However, the depths to which the faults propagate, and the dips associated with these faults remain unknown. Previous studies have applied elastic dislocation models to constrain the depth and geometry of faults in the subsurface [1,3-4].

The aim of this study is to first examine the variability of wrinkle ridge morphology within individual ridges, and then apply a simpler geometric approach to constrain the geometry of faults. We find that ridge morphology can vary significantly within a single ridge. Most ridges demonstrate a topographic step and have profiles consistent with a steepening of the fault dip at shallow depths.

Methods: Using Mars Orbiter Laser Altimeter (MOLA) topography data, the morphology of a set of ridges in Solis and Lunae Plana was analyzed through hundreds of profiles produced perpendicular to the ridges. The profiles for a given ridge were then grouped into clusters of similar morphology using a *k-means* classification algorithm, which iteratively adjusts the clusters based on the RMS difference between each profile and the average profile of the clusters. By assigning three or four distinct groupings, the variability in the morphology of individual ridges becomes clear. The average profiles of the clusters can be classified according to common morphological types as symmetric, asymmetric ramp, and double ridge (Fig. 1). Double ridges are classified as having asymmetric forelimb and backlimb, with a secondary ridge (also described as a broad arch and narrow ridge, or primary and secondary antiform) [1,3-5].

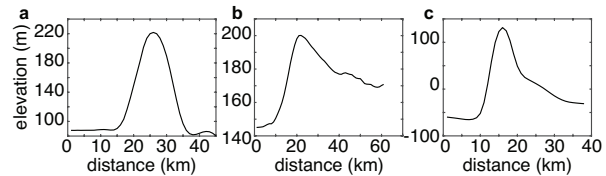


Fig. 1. Three common classifications of wrinkle ridge morphology. Symmetric (a), asymmetric ramp (b), double ridge (c).

When ridges display a step-like topographic offset, the underlying substructure can be inferred using a simple geometric model. The step across the ridge h_1 is a simple function of the fault offset d and dip θ_1 across the primary thrust fault at depth. We then assume that the height h_2 of the narrow wrinkle ridge is a result of a steepening of the dip in the shallow subsurface to θ_2 , as commonly inferred in modeling studies [1,3]. Assuming that the fault displacement is conserved across the change in dip, the relative dips of the two fault segments can be calculated from:

$$h_1/\sin(\theta_1) = h_2/\sin(\theta_2)$$

This analysis provides a simple calculation for the possible fault dips underlying the ridges.

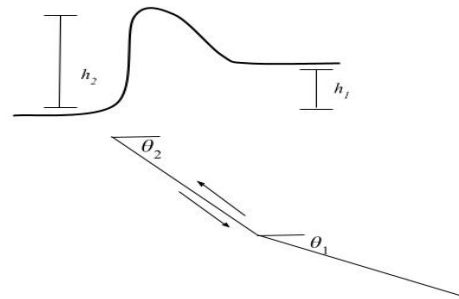


Fig. 2. Simple geometric model of a wrinkle ridge substructure relating a wrinkle ridge's offset, height, and dips of the shallow subsurface and primary thrust at depth.

Results: Morphology. We find examples of both ridges with consistent morphology throughout, as well as ridges that change morphology along strike. Ridge 220 in Solis Planum demonstrates consistent morphology along strike, with a symmetrical morphology with its forelimb and backlimb slopes

being near identical throughout all profiles on the ridge. Ridges also may have a constant morphology but vary in ridge height. Ridge 175 displays asymmetric ridge morphology throughout all clusters but varies in height by more than a factor of 1.5. In contrast, some ridges show significant changes in morphology along strike. Ridge 178 in Solis Planum changes from an asymmetrical ramp morphology to a simple step, to a double ridge morphology. This ridge also exhibits a drastic change in ridge height, varying from 90 m to 210 m (Fig. 3). The variability in both height and morphology within a single wrinkle ridge indicates that analyses based on one or a small number of profiles may not yield representative results.

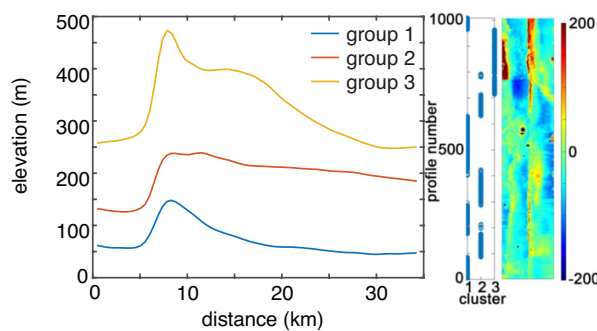


Fig. 3. Ridge 178 alters morphology from asymmetrical ramp to simple step, to double ridge (left) with color plot demonstrating location of each cluster with respect to the ridge (right).

Structure. Over 70% of ridges examined demonstrated a topographic step across the ridge. We first consider a typical wrinkle ridge with an asymmetric ramp morphology and a topographic step. Ridge 174 has a ridge height of 110 m and a step of 96 m. Assuming a lower fault dip of 30° , this requires a modest steepening of the upper fault to 35° . However, some ridges have a sufficiently small topographic steps relative to the ridge height that no solution exists if the lower fault dips at 30° . For example, ridge 1177 has a ridge height of 85 m and a step of 10 m. For our simple geometrical model, the maximum allowable lower fault dip is 7° for a vertical upper fault.

Wrinkle ridge 177 in Solis Planum exhibits a constant offset of ~ 70 m in all three of the sorted cluster groups. However, this ridge varies significantly in its height (100–233 m) despite the near constant step (Fig. 4). For this ridge, a lower fault dip of 30° cannot satisfy the ridge height for any upper fault dip. Assuming a smaller lower fault dip of 15° , we find upper fault dips ranging from 21° to 59° . The variability in the ridge height for a constant step across the ridge in this case

indicates that ridge height is a poor proxy for horizontal shortening in some cases, likely due to variability in the upper fault dip.

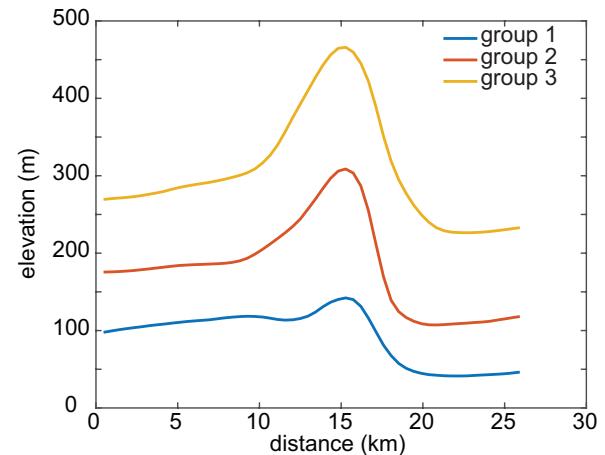


Fig. 4. Profiles of ridge 177 in Solis Planum show a wide range in ridge heights (100–195 m) for a relatively constant topographic step across the ridge (~ 70 m).

Conclusions: We find that most wrinkle ridges in Solis and Lunae plana on Mars can be classified into three distinct morphological types: symmetric, asymmetric ramp, and double. Ridge morphology can vary widely within a single ridge, with ridges demonstrating more than one morphological type throughout. While most ridges exhibit a clear topographic step, others do not. Simple geometrical models can provide insight to the underlying subsurface structure of ridges that exhibit this topographic step. Ridges with an offset provide strong evidence for a steepening of the fault dip at shallow depths, and in some cases require a lower angle ($<30^\circ$) dip on the lower faults and/or rather steep upper fault dips. In some cases, ridge height is a poor proxy for shortening, since ridge height can vary widely within a single ridge while maintaining a uniform step across the ridge. While wrinkle ridge topography can be used to elucidate subsurface structure, these observations suggest caution should be used when interpreting small numbers of ridge profiles.

References: [1] Watters T. R. (2004) *Icarus*, 171, 284–294. [2] Golombek M. P. et al. (2001) *JGR*, 106, 23,811–23,821. [3] Andrews-Hanna J. C. (2020) *Icarus*, 351, 113937 [4] Okubo C. H. and Schultz R. A. (2004) *Bull. GSA* 116, 594–605. [5] Watters T. R. (1988) *JGR*, 93, 10,236–10,254.