ORIENTATIONS AND MORPHOLOGY OF LINEAR RIDGES IN NILI FOSSAE: MINERALIZED FRACTURE ZONES AND IMPLICATIONS FOR CRUSTAL FLUID TRANSPORT.

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Introduction: Among the complex and diverse landforms in the region around Nili Fossae, Mars are linear ridges tens of meters high and several hundred meters in length (Fig. 1). The ridges are pervasive in the region and were first recognized in Mars Orbiter Camera (MOC) images where their morphology and location on the floors of some craters led [1] to propose they may be breccia dikes. With new data from the Mars Reconnaisance Orbiter (MRO) we have undertaken a thorough examination of these ridges in context of the evolving understanding of this region's diverse mineralogy, geology, and fluvial history [2,3,4,5].

The formation of ridges observed on Mars has been attributed to a variety of processes including exhumed igneous dikes [6,7,8], impact-generated pseudotachylyte and breccia dikes [1], eskers [9], and inverted fluvial channels [10]. We expand the analysis of ridges in Nili Fossae using detailed mapping of ridge orientation and morphology in an area densely populated with ridges to test the various mechanisms of formation.

The Nili Fossae graben formed during late-stage flexural deformation after the Isidis impact [11] on a timescale comparable to the lifetime of hydrothermal systems generated by basin-scale impact events [12]. Hydrothermal fluid circulation likely contributed to alteration throughout the region evidenced by the detection of zeolite, serpentine, silica, illite, and carbonate exposures in bedrock and olivine-bearing melt sheets [5,13]. Similar low-grade metamorphic assemblages have been reported in terrestrial impact deposits, as in the Ries suevite where intense alteration has been attributed to vertical channels that served as conduits for hot steam circulation [14]. In concordance with detailed observations presented hereafter, we propose that networks of ridges observed in the recessive phyllosilicate-bearing bedrock in Nili Fossae represent the expression of fractures that facilitated channelized fluid flow, were preferentially hardened through mineralization, and later exhumed by differential erosion.

Methods: The study area is shown in Figure 1 and was defined on the basis of previous observations of exposed ridges in the heavily eroded terrains near Jezero Crater [3,4,13]. Ridges in the study area (~4.5 x 10^4 km^2) were mapped using images from the MRO Context Camera (CTX, ~5 m/pxl) imported into ArcGIS and viewed at maximum resolution. Mars Odyssey Thermal Emission Imaging System (THEMIS, 230 m/pxl) global mosaics and Mars Orbiter Laser Altimeter DEMs (MOLA, 128 pxl/degree) were used for regional context and High Resolution Imaging Science Experiment (HiRISE, ~1 m/pxl) for detailed analysis.

Criteria were developed for consistent mapping of ridge features to avoid including other morphologies such as dunes or scarps in the analysis. Ridges were defined as sharply tapered linear to curvilinear features with large aspect ratios that express positive relief and produce shadows visible at CTX resolution. Linear features too small to resolve were omitted, unless clearly part of a developed array of larger ridges. When two or more ridges overlapped, individual ridge segments were defined as features that were continuous along strike even when intersecting other ridges. Ridges that appeared to abruptly change direction (see white arrow in Fig. 1b) were counted as two segments.

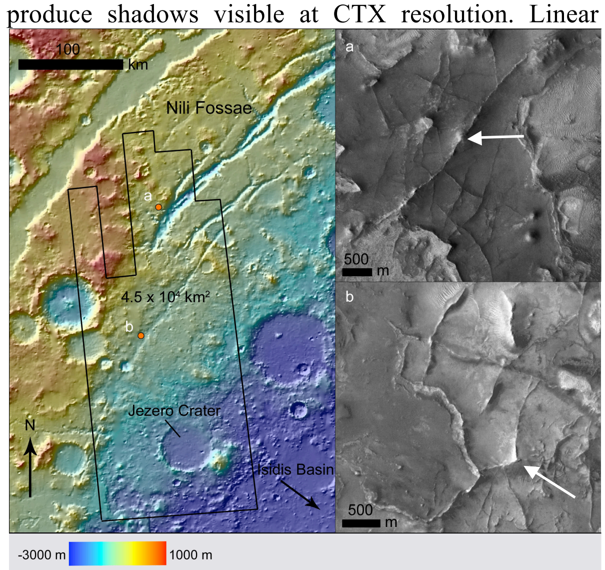

Figure 1 – MOLA DEM with study area outlined in black. Orange dots correspond to insets (a) and (b) which show examples of ridges. (a) P17_007569_2022_XI, (b) P17_007780_1987_XI. Arrows point to associated domical structures.

The strike of ridges was calculated using a simple MATLAB program which created a vector from the start and end points of each ridge segment and measured its orientation relative to 0° North.

Results: A total of 2283 individual ridge segments were mapped (Fig. 1). Most of the ridges are hundreds of meters in length, with an average length of 431.2 m and maximum length of 3.83 km (Fig. 2c). The width of individual ridges ranges from smaller than the spatial resolution of CTX to no greater than 20 meters. The ridges often occur in intersecting swarms (Fig. 2b) forming polygonal arrays, with larger ridges often bifurcating and anastamosing into branched networks. Longer ridges are sometimes associated with domical structures tens of meters in diameter (Fig. 1a,b), from which the ridges appear to emanate. HiRISE imagery shows that the ridges are made of indurate materials that erode into rocky talus.

Exposure of ridges in Nili Fossae is restricted to the oldest exposed stratigraphic unit, the smectite-rich Noachian crust identified by previous investigators [3,4,5,13]. Ridges are not expressed in the overlying mafic cap and olivine-carbonate units and are often observed to terminate at the contact between the units. The stratigraphic confinement of the ridges to the phyllosilicate-bearing crust suggests the ridges were emplaced prior to the olivine unit or that rheological differences between the two units influenced the formation and expression of ridges.

The ridges have a weak preferred orientation centered at approximately 58° azimuth with few ridges oriented around 0° (Fig. 2a). The orientation of the major troughs of Nili Fossae are plotted for comparison. There is a weak size-dependence of orientation where larger ridges (>750m) are slightly more concentrated around the statistical mean, but the orientation distribution remains more or less consistent at different length scales. The correspondence of the ridge orientations with the Nili Fossae graben suggests the influence of a common stress field.

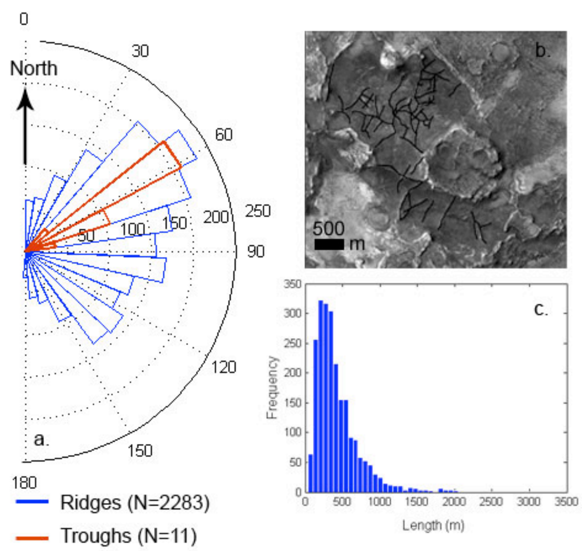

Figure 2 - a. Orientation-frequency of 2283 ridges and troughs in the study area. b. CTX image PSP_01920192 showing a mapping example. c. Length-frequency distribution of ridges.

Discussion: We favor the hypothesis that ridges are mineralized fracture zones or relict conduits of fluid flow that were established by impact-generated joints in the crust, or by extensional stress during flexural readjustments due to loading after the Isidis impact. The zones of concentrated flow were sealed, and preferentially hardened relative to the clay-bearing host rock. The ridges are exposed by differential erosion. The fluids necessary to harden the fractures may have come from pore fluid in the host rock or bound water in hydrated minerals, assuming that the alteration to clay preceded Isidis. In the latter model, some of the scatter in the orientation data can be accounted for by multiple generations of fracture where earlier random fracture was facilitated by dehydration embrittlement of clays, which were then overprinted by Isidis-radial stress due to flexure of the crust. Basin-scale impacts have the potential to remain hot for millions of years after the impact [12], providing a mechanism to drive hydrothermal circulation through the crust. In terrestrial craters subsurface hydrothermal fluid circulation has been shown to persist late in the impact sequence in the fractured basement beneath melt sheets [14] and ergo may have affected the carbonate-bearing unit and other hydrothermal assemblages observed around Isidis. The contact between the carbonate-bearing unit and the superimposed unaltered mafic unit may represent an aquatard where the upward circulation of fluids was hindered.

The lack of expression of ridges in the olivine-carbonate unit can be accounted for by three explanations: the fractures developed before the overlying unit was emplaced, differences in rheology lead to different deformation mechanisms at the time of fracture, or there was a lack of fluids in the olivine-bearing unit to seal the joints. In the first scenario, the opening of cracks and sealing with fluids occurred before the Isidis impact, possibly related to cooling of the crust. In the second explanation, which is favored, the first generation of fractures occurred at an earlier stage of deformation during the impact sequence than the deformation that produced the radial graben. If the olivine-bearing unit is a preserved impact melt [4] then it may have been too hot and non-viscous at this earlier stage of deformation to accommodate brittle failure and fracture was limited to the cold underlying bedrock.

The ridges in Nili Fossae represent fractures formed subsequent to the Isidis impact that were conduits for fluid flow, hardened and mineralized by circulating fluids, and later exhumed by differential erosion. The seams may have provided stable zones of high water activity and thermal energy potentially serving as a habitable environment. Future work includes mapping of ridge exposures elsewhere around Isidis Basin, incorporating CRISM analysis, and assessing the habitability potential.

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