LITHOLOGICALLY DIVERSE YARDANGS IN THE CIRCUM-ISIDIS REGION: IMPLICATIONS FOR YARDANG EVOLUTION CONTROLS AND IN SITU STUDY AT THE MARS 2020 LANDING SITE.

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Introduction: Parallel, wind-carved ridges called yardangs are pervasive features on Mars [1], with rare and hypothesized occurrences, respectively, on Earth and Venus. Despite recent advances in quantitative study of terrestrial yardangs [2], much remains unknown about the controls on yardang formation and evolution on planetary surfaces, including the combined influences of substrate friability, material heterogeneity, and structural bedding orientation on the morphologies of yardang fields from initiation to demise [2–4]. The rarity of yardangs on Earth and data limitations on Mars have restricted insight into the interplay of the diverse factors in yardang development.

The circum-Isidis region of Mars, including Nili Fossae and Libya Montes, hosts a lithologically and structurally diverse stratigraphy of Hesperian- to Noachian-aged rocks [5,6] that has been previously suggested to have eroded into yardangs. For instance, qualitatively parallel ridges that are nearly ubiquitously associated with a circum-Isidis olivine-rich unit [7] have been locally interpreted as yardangs [8,9]. Parallel ridges are common in the landing site for the Mars 2020 rover at Jezero crater and in potential extended mission targets in NE Syrtis [10]. The potential existence of yardangs eroded from the region's lithologically and structurally variable stratigraphy makes the region's geomorphology valuable for constraining substrate influences on yardang evolution. However, it remains unclear whether these features are yardangs or are other erosional, depositional, or structural features.

Methods: We constrained the origin of qualitatively parallel ridges in Nili Fossae and Libya Montes through measurements and observations using CTX imagery mosaics [11] and HiRISE imagery and digital elevation models [12]. We mapped the extent of potential yardang fields (Fig. 1), tested the potential yardangs' degree of consolidation with observations of rock textures, and tested whether they are bedforms by comparing their stratigraphic position and orientations with previously identified bedding. We also measured orientations of thousands of ridges, which we compared with those of adjacent crater wind streaks.

Results: *Ridge Classification.* We observe several types of parallel ridges in the circum-Isidis region. Libya Montes hosts the following ridge types associated with the olivine-rich unit: 1) large (10s to 100s of meters) inverted ship-hull ridges (Fig. 2), 2) small (meters to 10s of meters) elongate mounds, and 3) large (10s of meters) low-aspect-ratio mounds. These features variably qualitatively resemble "whale-back," "saw-tooth," or "hogback" yardangs [4].

In Nili Fossae, ridges are commonly 100s of meters in length and have high aspect ratio, irrespective of their association with the olivine-rich unit (Fig. 3), mafic capping unit, or Jezero delta (Fig. 4), resembling "long-ridge" yardangs [4]. Ridges in the floor material of Jezero, which includes a rock unit correlative with the olivine-rich unit [14], resemble other Nili Fossae ridges but have lower relief and shorter lengths (Fig. 4B,D). Ridges composed of basement rock in NE Syrtis, referred to as "Long Linear Features" [15] exhibit a paired-ridge, branching morphology strongly dissimilar from yardangs observed on Earth or Mars and are not considered further.

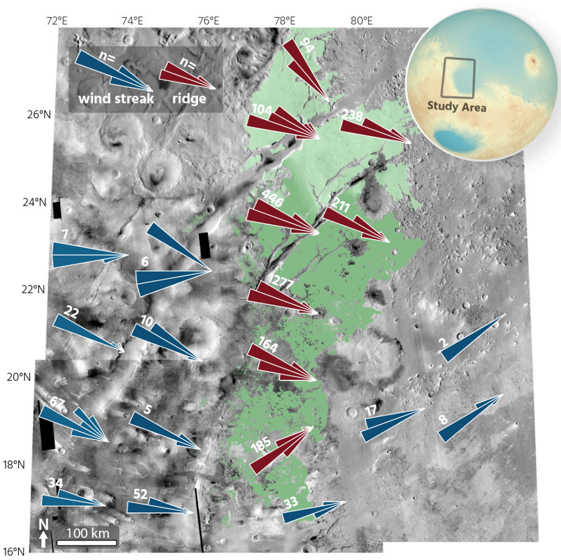

Figure 1: *Orientations of parallel ridges and wind-streaks in the Nili Fossae region. Orientation of winds eroding ridges may be interpreted as parallel to wind directions or 180° opposite. Potential yardangs are most commonly associated with the olivine-rich unit (green, after [13]). Libya Montes data not shown.*

Texture. Ridges associated with the olivine-rich unit in Nili Fossae and Libya Montes commonly exhibit meter-scale polygonal fractures characteristic of in-place exposures of the olivine-rich unit [7]. In general, the ridges exhibit the jagged, irregular topography of in-place bedrock instead of the smooth features of wind-blown sand. Boulders several meters in diameter are commonly observed on the flanks of the ridges.

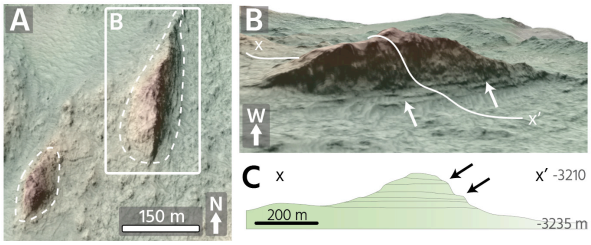

Figure 2*: Typical ridges in Libya Montes in (A) plan-view, (B) oblique view, and (C) cross-section. Note internal bedding (arrows) visible in B and C. (HiRISE stereopair ESP_016034_1835 and ESP_017089_1835).*

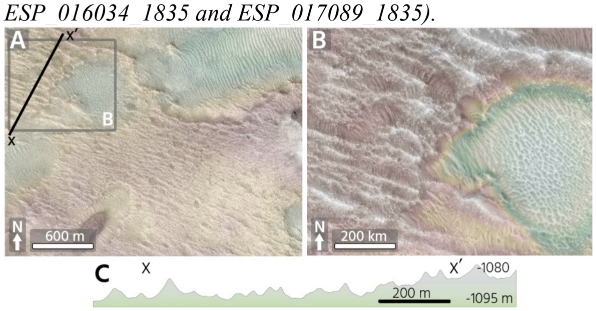

Figure 3*: (A) Typical parallel ridges in Nili Fossae showing (B and C) rugged morphology. (HiRISE stereopair ESP_032161_2015 and ESP_032161_2015.)*

Relation with Bedforms. In olivine-rich unit exposures in Nili Fossae and Libya Montes, ridges are composed of layered bedrock (Fig. 2). Many individual ridges in Nili Fossae are composed of both the lithologically distinct olivine-rich unit and mafic capping unit. Ridges are also observed on the rims of craters in northern Nili Fossae. In Jezero, the ridges exhibit no association with the more sinuous exposures of internal stratigraphy within the western delta. These observations collectively indicate that that these ridges are not bedforms but rather are erosional features.

Orientation. In Nili Fossae (Fig. 1) and Libya Montes, the ridges exhibit similar (northwest-southeast in Nili Fossae, north-south in Libya Montes) orientations, irrespective of their inferred lithologic composition, and are generally consistent with unidirectional winds blowing up and out of the Isidis basin. Ridges in NE Syrtis and Jezero's western delta and floor are also parallel with each other and adjacent wind streaks.

Discussion: Our work shows that the parallel ridges in the circum-Isidis region: 1) qualitatively resemble previously identified yardangs on Mars and Earth, 2) occur in bedrock rather than unconsolidated sediment, 3) are erosional landforms instead of bedforms, and 4) are locally and regionally parallel with each other and wind directions inferred from wind streaks. This evidence collectively indicates that these ridges are most plausibly interpreted as yardangs. Yardangs occur in four distinct, potentially sedimentary rock units: the olivine-rich unit, mafic capping unit, and Jezero delta, as well as the Jezero floor units. The lithologic diversity of yardangs, the conspicuous absence of yardangs in other seemingly friable units in this stratigraphy, and the wide range of structural bedding orientations [13] imply that yardang height, aspect ratio, and spacing may be measured to test for correlation with substrate lithology, bedding orientation, and other properties inferred from orbital imagery. Nili Fossae and Libya Montes may therefore provide valuable data in constraining the influence of substrate properties on yardang evolution.

Implications for Mars 2020: Yardangs in the western delta and floor of Jezero may be studied in situ by the Mars 2020 rover, and yardangs in Northeast Syrtis could be studied in a potential extended mission, allowing for measurements of bedrock and environmental controls on yardang evolution. Exposure ages estimated using yardang heights and orbitally measured local denudation rates [16] suggest that the delta's exposure age (300 Kyr - 200 Myr) is sufficiently young to preserve potential biosignatures [17], and exposure age estimates from yardangs elsewhere in the traverse may be calibrated with in situ radiometric ages.

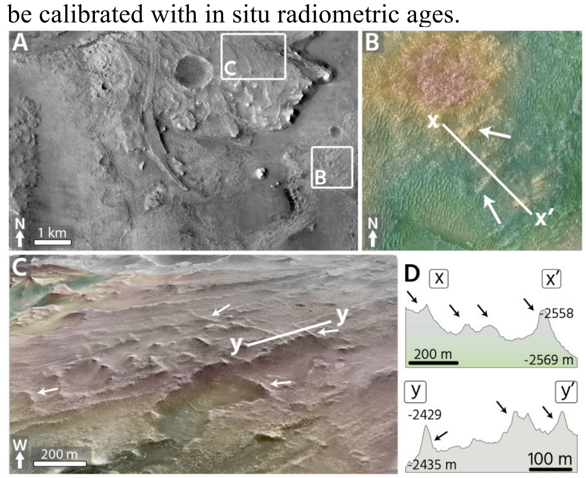

Figure 4: *(A) CTX mosaic of Jezero western delta and floor units. (B) Ridges associated with floor units. (C) Ridges associated with delta. (D) Ridge cross sections (from HiRISE stereopair ESP_046060_1985 and ESP_045994_1985)*

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