YARDANG FORMATION AND EVOLUTION IN A HYPERARID DESERT: THE INFLUENCE OF MULTIPLE WIND DIRECTIONS AND IMPLICATIONS FOR MARS. L. Kerber[1], J. Radebaugh[2], J. Rabinovitch[1], D. S. McDougall[2], J. M. Sevy[2], [1]Jet Propulsion Laboratory, Caltech University, 4800 Oak Grove Dr. Pasadena, CA 91109, USA (kerber@jpl.nasa.gov), [2]Department of Geological Sciences, Brigham Young University, Provo, UT 84602, USA.

Introduction: Yardangs are streamlined features formed through the action of wind erosion, common on Mars and in barren, arid deserts on Earth [1-2]. Yardangs are thought to indicate mostly unidirectional wind regimes, and their orientations have been used to ground-truth wind models in places where surface wind information is not available (such as on Mars) [3,4]. However, predicted wind directions have often been at odds with yardang orientations, leading some to suggest that yardangs were controlled by structure or paleowinds [3], or that wind model domain topography is insufficiently detailed [4]. This work focuses on the effects of multiple wind directions on yardang morphology and how it can be recognized both in the field and remotely.

Campo de Piedra Pomez is a yardang fleet located in the high Puna plateau of the Argentinian Andes near the town of El Peñón in the Catamarca Province. The yardangs are carved into an ignimbrite deposit from the 70-13 kyr eruptions of the nearby Cerro Blanco volcano [5]. Isolated from the effects of rain, this yardang fleet is an ideal place to study the effects of wind direction variations on yardang morphology.

The yardangs are oriented in a NW/SE direction with bows towards the NW (315-320°). During a Dec. 2018 field season, evidence for a secondary wind was documented in the form of stone wind-indicators called dedos, centimeter-scale erosional remnants that point in the direction of the impinging wind [6]. A strong, saltation-inducing secondary wind was experienced by the field team during one day of the field study [6]. During the 2019 field season, anemometers, tuft nets, and smoke flow tracers were deployed around a solitary yardang to document the primary and secondary wind directions and their effect on yardang morphology. Broader trends in yardang morphology were studied using dedo orientations and satellite imagery, in order to better interpret morphological clues provided by yardangs for the benefit of wind determination on Mars.

Methods: *Dedo Characterization:* The field team selected 26 yardangs spread throughout the fleet, including 20 yardangs along a transect from the leeward to windward side of the flow field (based on the dominant wind direction suggested by the primary yardang orientation). To determine the flow direction on each individual yardang facet, the team examined the dedos on the flanks of the yardangs in detail to determine the direction of the wind during erosion events. The average length of the dedos at the windward stagnation point was also measured to understand differences in wind erosion from the windward to leeward side of the fleet. For each yardang, the overall heading was measured with a Brunton compass, and then each yardang facet was characterized from bow to stern. Detailed dedo orientations were measured for 4 yardangs (up to 80-90 per yardang) using a digital compass-clinometer app called Fieldmove Clino (**Figure 1**).

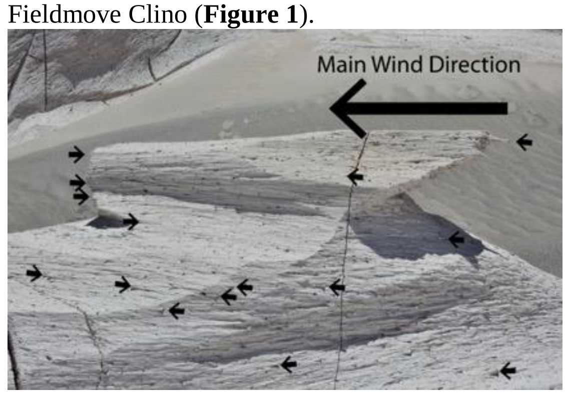

Figure 1. Evidence for erosion from a secondary direction was clear from the orientation of dedos.

Anemometer Measurements: Wind around a solitary yardang was measured for five days in 2019, with six Kestrel anemometers on rotating wind vanes placed (A) upwind from the bow, (B) port side (C) on top of the yardang, (D) starboard side (E) right at the stern and (F) significantly downwind (**Figure 2**), measuring wind every 30 seconds as well as temperature and pressure.

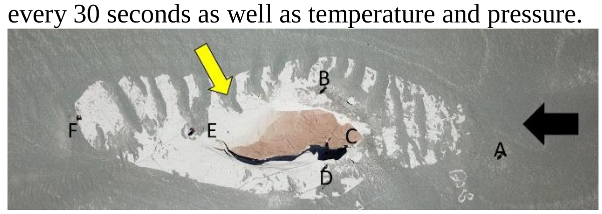

Figure 2. Location of anemometer array used to measure wind around a solitary yardang. Black arrow denote primary wind direction; yellow arrow denotes secondary wind direction. A facet has been cut in the yardang flank by the secondary wind.

Flow Visualization: Flow was visualized with colored smoke when primary and secondary winds were actively blowing to assess the strength and direction of secondary and reverse flows (**Figure 3**). Small nets (approximately 1 m x 1 m) with yarn tufts were placed on different parts of the yardang and filmed with timelapse cameras to show how the wind flowed across the surface and compared with dedo flow indicators.

Figure 3. Flow visualization using smoke tracers showed an alignment between the observed secondary wind direction, dedos, and a facet cut in the back of the yardangs in the areas.

Observations: *Dedo Characterization:* Evidence was found for dedos in many different directions, sometimes governed by the bending of primary flow around the yardang structure and sometimes by the presence of the secondary wind.

Wind Direction. During both field seasons, winds were calm in the morning and strong in the afternoons. In Dec. 2019, the wind came almost entirely from the secondary direction, matching the dedos on the back sides of the yardangs (**Figure 4**). In Dec. 2018, the wind came from the primary wind direction, accompanied by large dust devils which lofted fine sediment to substantial heights even when the ambient winds were not otherwise strong enough to saltate grains.

Flow Visualization: The 2019 flow visualization was consistent with results from dedo measurements on the back flank of the yardang (**Figure 3**). Flow visualization from tuft nets on the prow of the yardang did not match the direction of the dedos, indicating that these dedos were created by wind from the primary direction.

Conclusions: While the main orientation of yardangs in the CPP is controlled by a primary wind, the yardang morphology is also affected by a secondary wind. The presence of such winds can be inferred from orbit by the presence of yardangs without clear prows (**Figure 5**) or yardangs with facets cut in a consistent direction (**Figure 4**). In the Campo de Piedra Pomez yardang fleet, yardangs are influenced by at least two strong winds separated by less than 180°, and in another location by two winds separated by 90°.

Such morphologies in yardang fleets on other planets may be used to infer not just primary but secondary regional winds, for comparison with modeled local wind regimes [4].

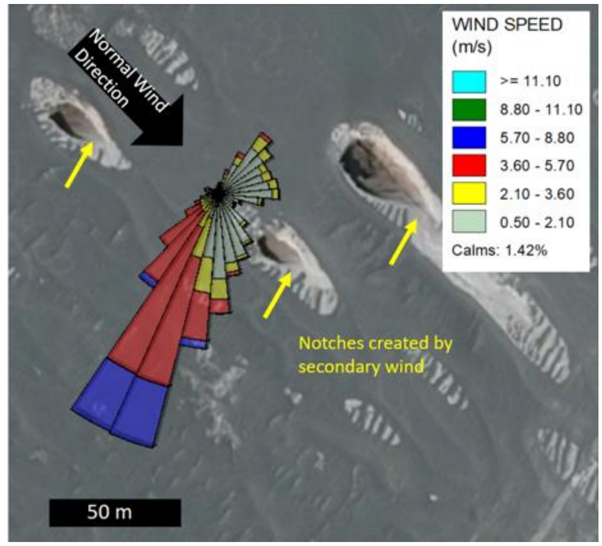

Figure 4. Wind measurements taken every 30 seconds over ~5 days from the anemometer placed upwind of the yardang bow. During this period wind was dominantly from the secondary direction.

Figure 5. (top) Yardangs exposed primarily to one wind direction, with prominent blunt windward prows (wind from top). (bottom) Yardangs exposed to two wind directions, without clear prows (wind from top and bottom). Yardangs are ~10 m wide.

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