WIND FLOW AROUND YARDANGS: IDENTIFYING MAJOR WIND DIRECTIONS FROM FLOW INDICATORS IN THE CAMPO DE LAS PIEDRAS POMEZ, ARGENTINA.

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Introduction: Yardangs, or wind-carved ridges, are thought to form in unidirectional wind regimes. Whitney [1] put forth a qualitative model to explain the flow of wind around a single yardang, principally based on the interpretation of aeolian flute directions on a single Egyptian yardang photographed by J.F. McCauley [1]. The model includes diverging flow around the nose of the yarding, and regions with separated/recirculating (reverse) flow eroding the flanks of the yardang. Ward and Greeley [2] visualized some amount of recirculating flow occurring at low wind speeds in wind tunnel experiments, but high wind speeds quickly eroded their fragile yardang simulants, meaning that they were unable observe the variation in the strength or presence of separated/recirculating flow regions under different conditions. They also did not observe recirculating flow around more blocky, less streamlined forms [2].

Yardang morphology can be affected by a number of factors, including 1) substrate hardness, 2) pre-existing fracture patterns, 3) consistency of wind direction, and 4) interference by other geomorphological agents, including rain erosion, dissolution, and flooding [3]. The Campo de las Piedras Pomez (CPP) yardang fleet, located in the Argentinian Puna plateau, is ideal for isolating the first three effects. It is a high-altitude, hyperarid desert with an annual rainfall less than 6 mm, and no evidence of water erosion in the yardang materials. For this reason, the morphologies of its yardangs have many similarities with those found on Mars [4]. This work focuses on the contribution of wind direction consistency on the morphology of yardangs. In this work, Whitney's [1] exercise of mapping small-scale flow indicators is repeated on dozens of individual yardangs evenly spaced along a transect from the windward side to the leeward side of the fleet. Observations made in the field focus on the influence of reverse flow induced by the yardang forms versus the influence of a secondary wind direction.

Field Site Description: The CPP yardang fleet is located in the Argentinian Puna near the small town of El Peñon, in the province of Catamarca (**Figs. 1-2**). At an altitude of 3,150 m (10,300 ft), the fleet is located on a high desert plain (with an atmospheric pressure near 0.7 bars).

The CPP yardang fleet is carved into ignimbrites sourced from the 70-13 kyr eruptions of the Cerro Blanco volcano (**Fig. 1**; [4]). While harder than many other yardang substrates (e.g., lacustrine and aeolianite; [5]), the ignimbrite is soft enough to be removed by scratching with the tip of a hammer. In a pioneering study, de Silva et al. [4] described how the material properties of yardangs (in this case, hardness and the presence of a capping layer), led to the formation of different sizes of yardangs found in the greater Argentinian altiplano. The yardangs of CPP are frequently characterized by a fine-grained, indurated capping layer underlain by a softer, more pumice-rich layer. The yardangs erode through a combination of abrasion and block collapse as the underlying layer is progressively undercut by aeolian abrasion, and blocks fail along pre-existing fracture networks [4]. These yardangs do not show evidence of any fluvial or pluvial processes. Instead, they are dominated by evidence of aeolian abrasion such as facets, flutes, and dedos (**Fig. 3**).

Methods: The field team walked a transect of the fleet from the leeward side to the windward side through the main body of yardangs (based on the dominant wind direction). To determine the flow direction on each individual yardang facet, the team examined "dedos"—finger-like projections of rock that point in the direction of oncoming wind (**Fig. 3**). Dedos form when hard lithic or pumice clasts, originally embedded in the ignimbrite matrix, shelter the softer ignimbrite behind them. Furthermore, each yardang facet was characterized from bow to stern for evidence of reverse flow.

Observations: The yardangs examined consistently displayed dedos conforming to the yarding geometry (as expected), and also displayed dedos oriented 180˚ apart. In many cases, local geometry that could induce flow separation and recirculation, allowed a dedo with the reverse orientation to be present in this recirculation zone. Also, it was observed that if the wind direction were to switch ~180˚, then this would expose the reverse-oriented dedos to this secondary wind direction, and protect the dedos oriented with the primary wind direction. This is consistent with the hypothesis, that, if multiple wind directions exist (even if there is a preferential primary direction), local flow separation can protect certain yarding facets and allow dedos to form in two opposite directions.

It is expected that the primary wind would be both the strongest wind encountered by the yardang as well as the wind carrying the most abrasive particles. For this reason, it was originally hypothesized that wind indicators such as dedos, would be more common and better developed on windward-facing facets compared to dedos on facets exposed to reverse flow. While this is generally true of dedos near the windward stagnation point of the yardangs, there was not an obvious dichotomy in the size or frequency of windward or reverse dedos on the yardang flanks. In some rare cases, dedos even pointed straight up or down, clearly following the wind as it flowed around the local irregular yardang geometries. These instances suggest that the impinging wind is strong enough to keep erosive particles aloft even as it bends around the yardang. Even so, many of the reverse flow indicators were extremely well developed, even in places that were sheltered by bluff upwind obstacles. The existence of a second wind, coming from nearly 180˚ degrees away, seemed necessary to form these dedos. In particular, evidence for reverse flow was strong on yardangs towards the leeward side of the fleet.

On the last afternoon of the field expedition, the dominant wind changed, and a strong wind came from the opposite side of the yardang fleet, driving thick saltation sheets into the leeward side of the yardang fleet and vaulting sand all the way up to the top of local yardangs in the direction hypothesized for the secondary wind direction. This wind continued for the entire afternoon. The guides, who frequently come to the Campo de Los Piedras Pomez, said that they had never in the course of their careers experienced wind from that direction, let alone of that strength.

Conclusions: While one wind direction is dominant in the CPP yardang fleet, a secondary wind is also present, producing yardangs towards the back of the fleet with blunt prows facing in both directions, and asymmetric morphologies with flow indicators highly correlated to local geometry. This secondary wind direction is not as strong as the primary wind direction, but it produces observable differences in yardang morphology that can even be seen from orbit.

References: [1] Whitney, M.I. (1983) *Eolian Sediments and Processes*, 38, 223-245. [2] Ward, A.W. and Greeley, R. (1984) *Geol. Soc. Am. Bull.*, 95, 829–837. [3] Kerber, L. et al. (2017) *Icarus*, 281, 200-219. [4] de Silva, S. et al., 2010, *Planetary and Space Science*, 58(4), 459-471. [5] Dong, Z. et al. (2012) *Geomorphology*, 139-140, 145-154.

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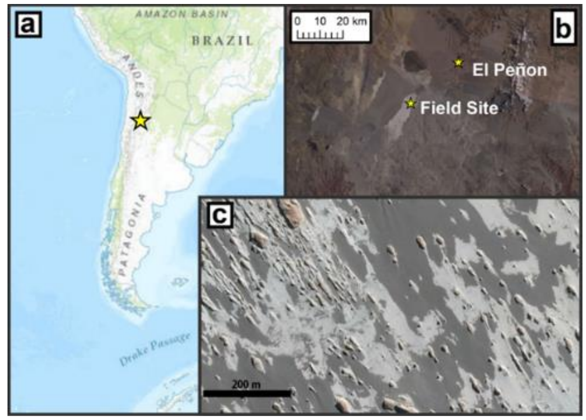

Figure 1 - a) Location of field site in Argentina (map from ESRI, Inc) b) The yardang field is carved into an ignimbrite deposit located in a desert valley between the source caldera, Cerro Blanco, to the southwest, and the town of El Peñon to the northeast (imagery from NASA, USGS, and ESRI, Inc). c) A close-up of the yardangs in the Campo de Piedra Pomez ignimbrite. (Imagery from CNES and Astrium via Google Earth).

Figure 2 - Campo de Piedra Pomez. The Puna is a hyperarid desert in the Andean rain shadow. The yardangs are carved into a small volume ignimbrite deposit erupted between 70-13 ka from the Cerro Blanco caldera complex (de Silva et al., 2010). a) A sparse yardang area. b) The field team walking through a yardang trough. c) A medium density yardang area.

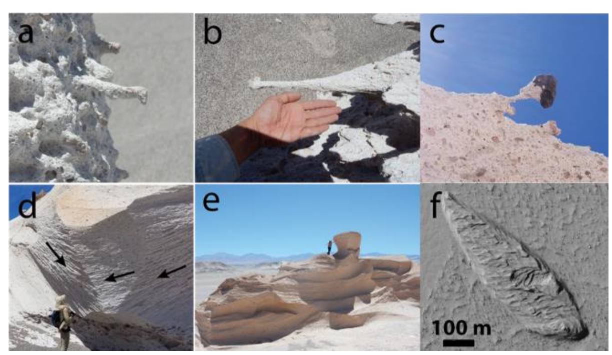

Figure 3 - Wind flow indicators. a-c) Dedos, created when a relatively more resistant clast (pumice in a-b, lithic in c) protects the fragile ignimbrite matrix behind it, resulting in a finger-like projection pointing into the wind. d) A yardang facet, showing the direction of the wind on each facet as recorded by dedos (local geometry allows dedos facing opposite directions to form on nearby facets). e) Facets on a yardang. f) Yardang facets on Mars.