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Formation of periodic bedrock ridges on Earth

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ABSTRACT

Periodic bedrock ridges (PBRs) are unexplained aeolian landforms discovered on Mars. PBR morphology and length scale resemble megaripples or small reversing dunes, but PBRs are eroded directly into bedrock. In this article we describe the first identified terrestrial PBRs from the Puna plateau of Argentina and present a hypothesis for their formation. The PBRs have formed in ignimbrite bedrock and are morphologically similar to nearby gravel megaripples. Observations along a landscape continuum provide basis for a genetic link between PBRs and gravel megaripples. First, gravel megaripples develop from lithics and pumice eroded from ignimbrite. The lithic clasts organize on the surface, forming megaripple crests and locally protecting the underlying ignimbrite. Exposed ignimbrite in troughs between the megaripples erodes and deepens as the ignimbrite topography evolves into a series of wind-transverse bedrock ridges (incipient PBRs) that mimic the pattern of overlying megaripples. The megaripples and incipient PBRs migrate downwind together and develop patterning indicative of bedform interactions with collisions, lateral linking, and ejections. PBRs emerge when the supply of lithics decreases and the crests become exposed by megaripple detachment. With crests exposed, PBRs appear to evolve into scalloped terrain due to abrasion. On Mars, the juxtaposition of megaripples and PBRs in some areas implies a similar evolutionary pathway whereby the megaripples seed PBR pattern. It may be possible for PBRs to develop through direct abrasion of bedrock; however, the mechanism(s) required to form wind-transverse PBRs as opposed to the more common wind-parallel features (yardangs) has yet to be identified.

1. Introduction

Periodic bedrock ridges (PBRs) are perplexing aeolian-derived ridges carved into bedrock. PBRs were first identified on Mars following the discovery of wind-perpendicular ridges exposing stratigraphy in the Valles Marineris and Medusae Fossae Formation (Montgomery et al., 2012). PBR morphology and length scale are similar to other wind-transverse granular bedforms on Mars such as megaripples and transverse aeolian ridges (TARs). In some areas on Mars, PBRs and other granular bedforms are found coincident. However, observations of exhumed bedrock stratigraphy confirm PBRs are distinctly erosional. The flow-transverse orientation of PBRs differs starkly from yardangs (streamlined wind-parallel aeolian erosion landforms found on Earth and Mars, e.g., Goudie, 2007; Ward, 1979; Barchyn and Hugenholtz, 2015). Yardangs are well studied and a common manifestation of aeolian abrasion on friable bedrock (Goudie, 2007; Laity, 2009). What causes the difference in orientation between yardangs and PBRs? Montgomery et al. (2012) suggested mm- to cm-scale transverse features that develop during abrasion or fluid stressing are potential analogs for the formation of PBRs, but scaling and mechanism details remain vague.

In this contribution, we present field observations and satellite imagery of PBRs in the Puna plateau of northwestern Argentina (Fig. 1). Previous work in this region has documented the largest wind ripples on Earth (Milana, 2009) and suggests it may be a potential analog for the Medusae Fossae Formation on Mars (Mandt et al., 2008, 2009; de Silva et al., 2013). The formation of the megaripples remains a topic of debate (Milana, 2009; de Silva, 2010; Milana et al., 2010; de Silva et al., 2013). They are partially carved into bedrock, suggesting that these features could be analogous to PBRs (Montgomery et al., 2012). This noted, most research in the Puna region has focused almost exclusively on megaripples, with only cursory description of the related bedrock patterning. In this article we describe, for the first time, the existence of a broad field of terrestrial PBRs that share many similarities with those found on Mars (Fig. 1). We use satellite- and ground-based data to outline a hypothesis for PBR formation. Prior to this, we outline the study site and previous work.

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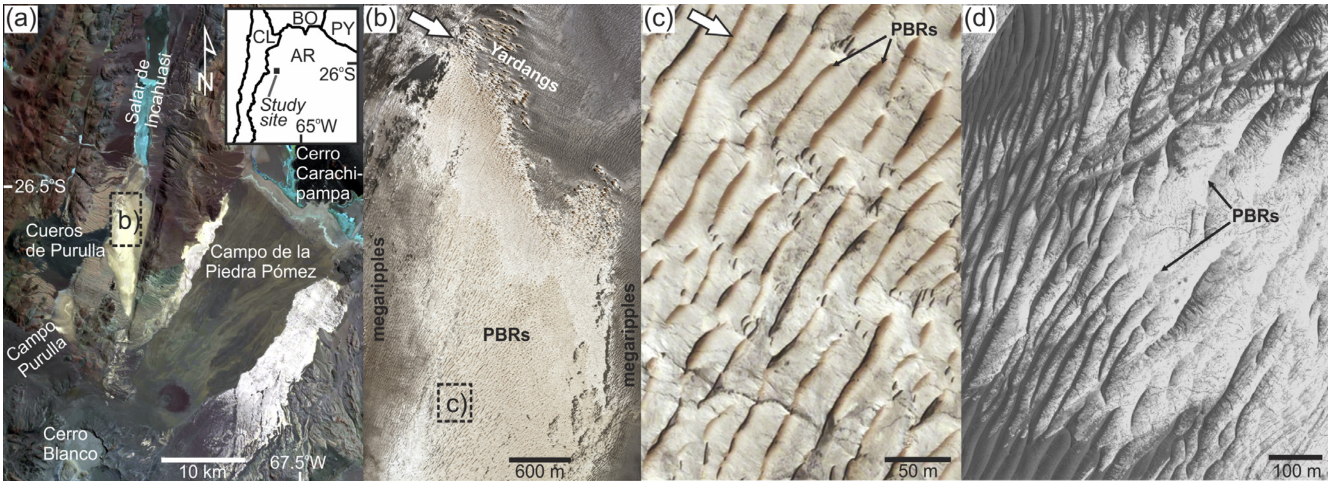

Fig. 1. (a) Satellite image showing the location of the main study site south of the Salar de Incahuasi. Nearby volcanoes (Cerro Blanco, Cueros de Purulla, Cerro Carachipampa), and key megaripple fields (Campo Purulla and Campo de la Piedra Pómez) are indicated. Inset map in (a) shows the location of the study site within Argentina. (b) QuickBird satellite image (0.5 m/pixel) showing megaripples and yardangs bordering the main exposure of PBRs. (c) Examples of PBRs with smaller megaripples in troughs and on crests. The broad, white arrows in (b) and (c) denote the dominant wind direction. (d) PBRs on Mars showing interplay between bedrock and megaripples in West Candor Chasma (HiRISE image PSP_006164_1750_RED, see Montgomery et al., 2012 for further examples).

2. Study site

This study examines PBRs carved into ignimbrite in the Salar de Incahuasi valley, located on the Puna plateau of Catamarca Province, northwestern Argentina (Fig. 1). The geology of the region has been reviewed by Kay et al. (2008) and is briefly summarized here to highlight key features. The valley is one of several regional sub-basins containing vast expanses of megaripples and exposures of ignimbrite. PBRs are located along the south end of the valley near the Cerro Blanco volcanic complex (see Pritchard and Simons, 2002; Arnosio et al., 2005). The western side of the valley in the vicinity of the PBRs rises ~1300 m above the floor and is flanked by the Sierra de Calalaste (~5050 m a.s.l.) and Quaternary volcanic deposits associated with the Cueros de Purulla obsidian lava dome, as well as the Late Miocene Rosada ignimbrite (8.1 ± 0.5 Ma, Kay et al., 2008; 6.3 ± 0.2 Ma, Kraemer et al., 1999). The western side of the valley is flanked by relatively steep slopes (~20°) rising ~500 m above the valley, exposing the Rosada ignimbrite and lower Paleozoic units (Kay et al., 2008). The floor of the valley dips north towards the large playa known as the Salar de Incahuasi (elevation drop ≈500 m/15 km, 3850–3350 m a.s.l.).

PBRs occur along the south end of the Salar de Incahuasi valley and are eroded into the Blanco ignimbrite (^{40}AR/^{39}AR age of 0.2 ± 0.1 Ma; Siebel et al., 2001). This ignimbrite has a rhyolitic composition (70–74.4% SiO_2) and is massive, crystal poor (quartz, plagioclase, and biotite), pumice rich, and poorly welded (Kay et al., 2008). The presence of pumice and lithic clasts produces a wide variation in the density of sediment released from the ignimbrite. In general, pumice clasts in the region are 25–50% of the density of the lithics (de Silva et al., 2013).

Several geomorphic and sedimentary features in the Salar de Incahuasi valley provide context for the PBRs and related processes (Fig. 2). First, a field of yardangs is present along the north end of the broad exposure of Blanca ignimbrite, indicating a long term transport direction on the west side of the valley towards the southeast (Fig. 2a), although on the opposite side of the valley the orientation of megaripples indicates topographic steering of transport winds towards the south–southeast (Fig. 2d). The yardangs have steep to overhanging stoss sides, and gentle downwind-dipping lee slopes. Second, there are vast pumice-rich deposits exposed at the surface in the main field of PBRs (Fig. 2b), indicating variations in ignimbrite depositional facies are common. Kay et al. (2008) also noted facies variations in the Blanca ignimbrite, ranging from co-lag proximal to distal pumice-rich. Third, there are several north-trending fluvial channels carved into the ignimbrite along the western edge of the valley in the vicinity of the PBRs (Fig. 2c). These channels represent influx pathways for sediment originating from adjacent valley slopes. They evolve into a complex of megaripple-covered alluvial fans north of the yardangs (Fig. 2d). In general, the channels and alluvial fans coincide with higher gravel cover at the surface.

There is a dearth of wind measurements for the area, although Milana (2009), de Silva et al. (2013), and anecdotal reports from locals suggest that extreme wind speeds occur in the region today. These interpretations contrast with wind speed measurements by Bridges et al. (2015) from March to November 2013 in the Salar de Incahuasi, which revealed daily averages ranging from 0.3 to 8.1 ms^{-1} and maximum daily gusts ranging from 3.1 to 25.0 ms^{-1}. The probability and frequency of aeolian sediment transport, although difficult to assess without direct measurements, has been previously considered by de Silva (2010) and de Silva et al. (2013). Each of these publications report a substantially different threshold wind speed at 2 m above the surface for 1 cm pumice clasts ($u_{t[2m]}$, 25 m s^{-1} and 17.5 m s^{-1}, respectively). To resolve the discrepancy, we performed calculations using the same equations (Shao and Lu, 2000; Law of the Wall) and parameterizations (elevation-adjusted air density: 0.7 kg m^{-3}; pumice clast density: 800 kg m^{-3}; surface roughness: 0.005 m). Our calculations indicate that $u_{t[2m]} \approx 15.04$–25.55 m s^{-1} (54.14–91.99 km h^{-1}) for 1–3 cm pumice clasts, respectively. For 1–3 cm lithic clasts (clast density for basalt ≈3000 kg m^{-3}), $u_{t[2m]} \approx 28.50$–49.39 m s^{-1} (102.60–177.82 km h^{-1}), respectively. These values are lower than previous estimates for pumice clasts, and if wind speed data reported by Bridges et al. (2015) are representative of winds in the Salar de Incahuasi valley, it is possible that 1–3 cm pumice clasts are occasionally mobilized by gusts, and that small (1 cm) lithic clasts are rarely mobilized. Note these calculations are for fluid entrainment, impacting pumice clasts are likely to advance lithic clasts.