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Evolution and diagnostic utility of aeolian rat-tails: A new type of abrasion feature on Earth and Mars

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ABSTRACT

Aeolian rat-tails (ARTs) are a previously undocumented, regionally-ubiquitous aeolian abrasion feature observed on matrix-supported ignimbrite surfaces in the Puna Plateau of Northwest Argentina. ARTs consist of an abrasion-resistant lithic clast projecting above the surface with a lee tail or 'keel' in the more erodible matrix. Size is controlled by the dimensions of the windward lithic clast, ranging from centimetre to meter scale; spatial density varies with clast content, which may reflect variations in ignimbrite facies. Field observations suggest ARTs follow a definable evolutionary sequence. First, an abrasion-resistant lithic clast contained within the ignimbrite is exposed to abrasion at the surface. Impacts from abrading particles erode the softer ignimbrite matrix adjacent to the clast. The clast shelters the leeward surface under a unimodal abrasion direction, creating a tail that tapers downwind and elongates as the clast emerges. Clasts become dislodged from the matrix as the surrounding surface erodes, ultimately destroying the feature if the clast is small enough to be mobilized directly by wind or impacting particles. This evolutionary sequence explains the morphology of ARTs and the presence of loose clasts on the ignimbrite surface, which contributes to the development of other landforms in the region, such as periodic bedrock ridges, yardangs, and megaripples. Satellite and rover images suggest similar features also exist on Mars. Because the formation and preservation of ARTs is contingent on unimodal abrasion direction, their orientation can be used as an indicator of long-term aeolian sediment transport direction.

1. Introduction

Aeolian abrasion is a form of mechanical weathering responsible for eroding and shaping extensive areas on the surfaces of Earth, Mars, and other planetary bodies. Abrasion landforms are most prevalent in dry and windy environments with a supply of sand-sized sediment that is (or was) mobilized by wind.

The Puna Plateau of Northwestern Argentina is an area extensively shaped by aeolian processes. Here, aeolian abrasion of ignimbrite bedrock has produced many enigmatic features: gravel-mantled megaripples, yardangs, and periodic bedrock ridges (Milana, 2009; de Silva et al., 2010; Barchyn and Hugenholtz, 2015; Hugenholtz et al., 2015). Abrasion textures, including, but not limited to, flutes, pits, and grooves, are widespread on exposed ignimbrite surfaces and ventifacts throughout the region.

Here we describe a previously undocumented abrasion feature observed on ignimbrite surfaces, referred to as an aeolian rat-tail (ART). ARTs are similar morphologically to glacial rat tails (e.g., Prest, 1983) and aeolian shadow dunes (Hesp, 1981); however, they are the result of very different processes. ARTs are a streamlined erosional feature characterized by a windward abrasion-resistant clast and a downwind-tapering tail carved from the erodible ignimbrite matrix (Fig. 1). The Mars Science Laboratory Rover Curiosity and Mars Exploration Rover Opportunity has photographed morphologically-similar features during investigations of the Sheepbed Mudstone formation at Yellowknife Bay in Gale Crater, as shown later in this paper (see Fig. 7) (Day and Kocurek, 2015), and the Burns formation in Meridiani Planum (Grotzinger et al., 2005, 2014; Stack et al., 2014). The common morphology suggests similar formative mechanisms and evolution patterns.

In this contribution, we present field observations and measurements of ARTs and propose an evolutionary sequence of their inception and demise. Like yardangs, ARTs appear to be diagnostic indicators of long-term aeolian sediment transport direction, but on a shorter timescale of erosion. They also provide new evidence regarding directional variability of aeolian sediment transport in the southern Puna Plateau.

2. Study area

The Puna Plateau lies to the west and in the rain shadow of the Andes, receiving little precipitation. The climate is thus semi-arid to

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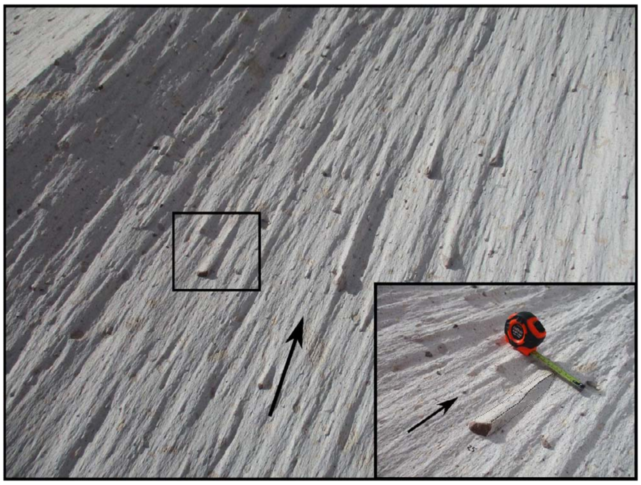

Fig. 1. An example of ARTs in the study area. Arrows indicate inferred abrasion direction. The ART shown in the inset image is 1.9 cm tall, 3.0 cm wide, and 9.6 cm long.

hyper-arid, varying with altitude and latitude (de Silva et al., 2010) (Fig. 2). Large expanses of ignimbrite (consolidated pyroclastic flow deposits) dominate the region's surficial geology (de Silva et al., 1989; Kay Mahlburg et al., 2008). Alluvial landforms exist in the region, attesting to episodes of pluvial and/or nival runoff (Hugenholtz et al., 2015); however, aeolian processes have produced the region's most enigmatic landforms: yardangs, periodic bedrock ridges, gravel-mantled megaripples, and sand dunes. Other prominent aeolian features visible from the ground include ventifacts and ARTs.

Two ignimbrites are present in the region: Blanca ignimbrite (^{40}AR/^{39}AR age of 0.2 ± 0.1 Ma; Siebel et al., 2001), and the older Rosada ignimbrite (8.1 ± 0.5 Ma; Kraemer et al., 1999; Kay Mahlburg et al., 2008; 6.3 ± 0.2 Ma). The Blanca ignimbrite is of rhyolitic composition and is pumice rich, crystal poor, and poorly welded (Kay Mahlburg et al., 2008). Facies variation within the Blanca ignimbrite has been noted, ranging from co-lag proximal to distal pumice rich (Kay Mahlburg et al., 2008). The Rosada ignimbrite was emplaced by a rhyodacitic ash flow, resulting in highly to moderately welded deposits that have moderate amounts of pumice, are crystal rich, and are poor in lithic fragments (Kay Mahlburg et al., 2008). These rhyolitic ignimbrites contain an estimated ~20% pumice clasts with densities ranging from 800 to 1300 kg/m^3 and ~10% by volume of lithic clasts, with densities 2600–3000 kg/m^3 (de Silva et al., 2013; Bridges et al., 2015), although local variations have been noted. The majority of observations presented in this report focus on ARTs carved from the Blanca ignimbrite.

The Puna Plateau suffers from spatially-constrained and temporally-limited wind measurements. Yardangs suggest a longer timescale regional wind pattern dominated by northwesterly winds. Site-specific wind data are sparse and largely anecdotal, but isolated field observations suggest saltation of sand-sized particles is common (Bridges et al., 2015). There are also reports from residents, and wind data from stations substantially outside the field area, suggesting that extreme wind events occur (Milana, 2009; de Silva et al., 2013). Bridges et al. (2015) installed instrumentation and logged wind speed from March to November 2013, reporting both daily average and peak gust speeds, and direction. The paucity of wind data and direct measurements make it difficult to assess the frequency and magnitude of contemporary aeolian sediment transport events and the present rate of landform evolution.

3. ART observations and description

Measurements and cataloguing of ARTs focused at three main study sites (Fig. 2): Salar de Incahuasi (SI), Abra Pómez (AP), Campo de Piedra Pómez (CPP). Altitudes ranged from ~3200 m in the CPP to ~4100 m in the AP. The morphology of ARTs was consistent throughout the region. Each ART was characterized by an abrasion resistant, windward lithic clast (the 'head') and a downwind-tapering tail. The clasts were composed of extrusive igneous rocks that ranged from granules (0.2 cm–0.4 cm) to pebbles (0.4 cm–6.5 cm), cobbles (6.5 cm–25 cm), and boulders (≥25 cm) (Wentworth, 1922). From a limited sample size ($n = 77$), we obtained measurements of the head height (H) and width (W), and the downwind length (L) of the tail (Table 1) using a tape measurer and ruler to millimeter precision. The smallest head height was as 0.3 cm, while the largest was 77.5 cm tall; tail length ranged from 1.3 cm to 350 cm. Typically, ARTs have tails that are 4 times longer than their height, with their head height and tail length positively correlated ($R^2 = 0.86$, $p < 0.01$). This suggests head height influences the length of the tail.

Some ARTs displayed concentric or horseshoe scour marks around the base of the head; others showed varying degrees of clast undercutting (Fig. 3). The largest boulders displayed well-defined scour

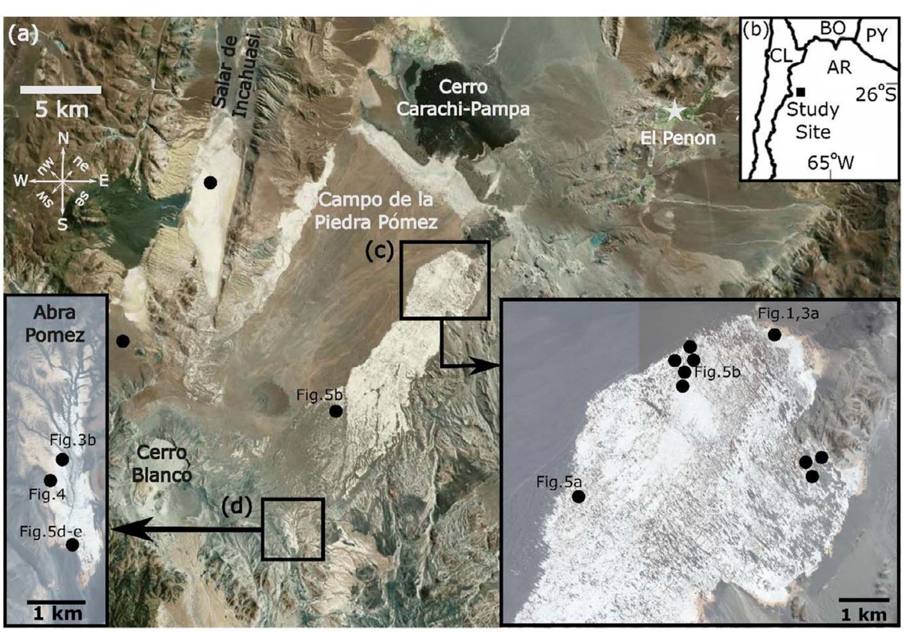

Fig. 2. **(a)** Overview of the study area and sampling points (black circles) where ARTs were examined on the Puna Plateau. (b) Inset map showing the location of the Puna Plateau in Argentina. The main field sites were located in the Salar de Incahuasi valley (SI), Campo de la Piedra Põmez (CPP), and Abra Põmez (AP). Nearby volcanoes (Cerro Carachi-Pampa and Cerro Blanco) are labelled. The locations of photographs shown in other figures are indicated by the figure number next to their marker. El Peñon is the closest inhabited village.