

GRAVEL-MANTLED AEOLIAN BEDFORMS FROM THE PUNA OF ARGENTINA: ORIGIN, CLASSIFICATION, AND RELEVANCE TO MARS S. L. de Silva¹, M. G. Spagnuolo², N. T. Bridges³, J. R. Zimelman⁴, E. M. Neely⁵ ¹College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331 (desilvas@geo.oregonstate.edu), ²IDEAN, UBA-CONICET Ciudad de Bs. As., Argentina, ³JHUAPL, Laurel, MD 20723, ⁴CEPS/NASM MRC 315, Smithsonian Institution, Washington D.C. 20013-7012. ⁵Department of Geology, Portland State University, Portland, OR 97201.

Introduction Gravel bedforms in the Puna of Argentina may be the most extreme aeolian bedforms on Earth and are potential analogs for aeolian processes on Mars [1-4]. Under the auspices of NASA Mars Fundamental Research Program grant NNX10AP79G we have used field observations, supplemented by experimental and numerical constraints on wind characteristics and aeolian transport, to reveal their conditions of formation and growth to be an aeolian geomorphology “perfect storm.” Although referred to as megaripples, the morphology and dynamics of these bedforms pose problems of classification. Nonetheless, these features provide some very useful insight into Mars aeolian processes.

A model for the origin of the Puna gravel mantle bedforms. The megaripples are coarse gravel-mantled bedforms with cores of sand and silt developed on eroded bedrock ignimbrite, aeolian erosion of which yields the bimodal association of dense ($\sim 2.4 \text{ g cm}^{-3}$) volcanic and metamorphic clasts and lighter pumice clasts ($\sim 1 \text{ g cm}^{-3}$) that makes up the gravels. Locally the gravels may be augmented by lithics from the surrounding basement. Field, experimental, and theoretical characterization of wind characteristics and aeolian transport in the Puna demonstrate the role that saltating sand and pumice plays in inducing lithic clasts to creep. The intimate association of pumice and lithics in the bedforms reflects this, with strong evidence that bedforms form by organization of the lag gravel into stable bedforms by creep of lithic clasts induced by impact of saltating pumice. An undulating topography on the bedrock ignimbrite also plays an important role in focusing bedform nucleation on upslopes and crests. The best-developed bedforms cap a topography with amplitudes as high as 2 m and wavelengths of 30 m or more, although the bedform itself makes up only ~ 30 cm of the topography. Because the transport and deposition of sand and gravel is decoupled, the sand/silt cores of the gravel mantled bedforms are interpreted to have been trapped by the gravels. Kinetic sieving of sand and silt through the gravel results in a gravel mantled bedform as the gravel pavement is lifted up by the growing sandy core. This model for entrapment, infiltration, and growth implies that cores of the megaripples are accreted over time after a stable gravel accumulation has developed. A role for “shadowing” in the growth of the megaripples is also likely.

Classification of the Puna gravel-mantled bedforms. Strong control by bedrock topography means that the largest bedform wavelengths are not a result of particle trajectories. Moreover, it appears that once formed the largest bedforms are stable and do not appear to migrate. They are dynamic in the sense that clasts are exchanged between bedforms, but the bedforms do not appear to move once formed unless disrupted by unusual wind characteristics. These two observations are in contrast to typical ripples. Further compounding the problem of classification is that while morphologically the Puna bedforms plot together in the megaripple cluster on Figure 1, they show a distinctive shift to larger width for the same aspect ratio of other megaripples, representing what seems like an end-member group between different-grainsize megaripples. Most interestingly, in size and aspect the Puna megaripples are morphologically and contextually similar to the small-scale TARs. Thus, genetically, dynamically and morphologically the largest features are not ripples in the sense of migrating bedforms, but rather nucleation sites of wind transported sediment. They appear to show more kinship to TARs on Mars and we speculate that they may represent the first recognition of TARs on Earth. As such, their stable yet dynamic character could help reconcile current models of martian TARs [7-9] with periodic bedrock ridges (PBRs) that may be produced by aeolian erosion [10] The flow separation model presented for PBRs is similar to the model proposed here for the development of the topography after mature Puna megaripples have formed. The presence of sediment capping some of these PBRs makes this analogy potentially even more compelling.

The Puna as a natural analog for Mars. Do these extreme, possibly unique bedforms tell us anything about Mars? Although such coarse bedforms have not yet been described on Mars, we find several themes where our observations of the Puna gravel-mantled megaripples are relevant. First, the Puna gravel bedforms consist of materials that have similar equivalent weight to those composing the granule ripples at Meridiani Planum, Mars. The Puna megaripples are composed of pumice of density $0.8\text{--}1.3 \text{ g cm}^{-3}$ capped by lithics with a density of $2.6\text{--}3 \text{ g cm}^{-3}$. For a cubic centimeter of material, this translates to a weight on Earth of $8\text{--}13$ and $25\text{--}29 \text{ mN}$, respectively.

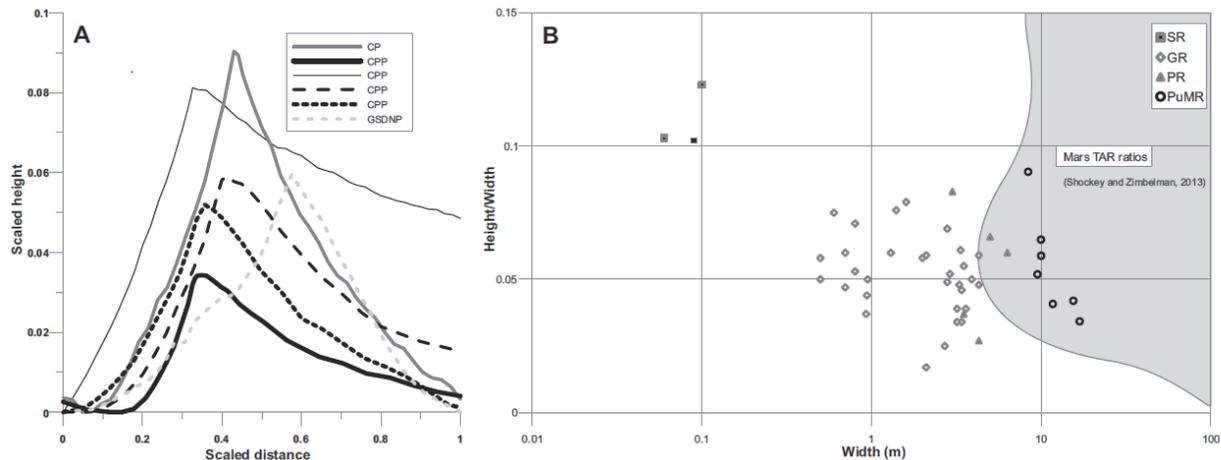


Figure 1. (A) Normalized profiles across gravel megaripples at Campo Purulla (CP) and Campo Piedra Pomez (CPP) fields and granule ripples at Great Sand Dunes National Park (GSDNP, Colorado, United States) for comparison, where both height and width are scaled by feature width (modified from [5]). Note the distinct difference in the symmetry of the ripples at CP versus CPP where the ripples are clearly asymmetric. (B) Scatter plot of feature height scaled by feature width, shown as a function of feature width using a logarithmic scale. Note the distinctive shift in the Puna megaripples (PuMR; this study) toward larger values in width with respect to the same aspect ratio of other megaripples reported by [5] (SR—sand ripples; GR—granule ripples; PR—pebble ripples). In size and aspect they are essentially the same as small transverse aeolian ridges (TARs) on Mars [6].

The Meridiani ripples consist of basalt ($\sim 3 \text{ g cm}^{-3}$) capped by hematite concretions ($\sim 4.9\text{--}5.3 \text{ g cm}^{-3}$ [11]), which, for a cubic centimeter of material, weighs 11 and 18–20 mN, respectively, on Mars. For such large particles, effects of particle friction Reynolds number and interparticle forces can be largely ignored, such that material weight is the main resistive force to the wind [12]. Therefore, the resistive forces for the ripple cores are about the same in the Puna and on Mars, with those for the capping materials slightly less on Mars. For equivalent weight materials, of which these more or less are, the threshold friction speed needed for movement is proportional to the square root of atmospheric density [13]. Taking atmospheric densities of 0.7 and 0.0154 kg m^{-3} for the Puna and Mars, respectively, results in threshold speeds that must be $\sim 7\times$ greater on Mars ($\sqrt{0.7 / 0.0154}$). Such high-speed threshold winds occur much less frequently on Mars [14] than they do in the Puna. Furthermore, the occurrences of excess shear stress (e.g., from velocities above threshold) are certainly much more common, and of greater magnitude, in the Puna than on Mars. Therefore, we can consider the Puna a good analog for Mars, but operative at rates that are probably much greater due to the generally higher frequency of threshold winds and both frequency and magnitude of winds above threshold. This is in large respect an advantage, as it represents Mars aeolian processes in “fast motion” that can be studied in situ. Taking the Meridiani values and factoring in martian gravity (0.38 that of Earth) means that a cubic centimeter of basalt on Mars has about the same weight as pumice on Earth. If we assume a density of $4.9\text{--}5.3 \text{ g cm}^{-3}$ for

hematite, its Mars equivalent weight for a cubic centimeter would be 1.8–2.0 mN, somewhat less than the 2.6–3 mN for the exotic lithics. The Puna therefore serves as a natural laboratory for Mars. In particular, our demonstration that the bimodal clast population of pumice and lithics is critical to the development of gravel bedforms and the impact of saltating (low-density) pumice is the main driving force for creep of the denser lithic clasts may be a useful analog for the development of Terra Meridiani ripples through basalt impact on hematite.

References: [1] Milana, J.P. (2009), *Geology*, 37, 343–346. [2] de Silva, S.L. (2010), *Geology*, 38, e218. [3] Milana, J.P. et al. (2010), *Geology*, 38, e219–e220. [4] de Silva, S.L. et al. (2013), *Geol. Soc. Am. Bull.*, 125, 1912–1929. [5] Zimbelman J.R. et al (2012) *Earth Surf. Proc. Land.*, 37, 1120–1125. [6] Shockey K.M. and Zimbelman, J.R., (2013) *Earth Surf. Proc. Land.*, 38, 179–182, [7] Balme, M.R., et al., (2008) *Geomorph.* 101, 703–720, [8] Zimbelman, J.R., (2010) *Geomorph.* 121, 22–29, [9] Berman D. C. et al. (2011) *Icarus*, 213, 116–130, [10] Montgomery, D.R, et al., (2012), *JGR*, 117, E03005. [11] Soderblom, L.A., et al., (2004) *Science*, 306, 1723–1726. [12] Kok, J.F., et al., 2012. *Reps. Prog. Phys.* 75, 106901. [13] Shao Y.P. and Lu, H. (2000) *JGR* 105, 22,437–22,443. [14] Haberle et al., (2003). *Icarus*, 161, 66–89,