MEGARIPPLES ON EARTH AND MARS CAN UNIQUELY BE IDENTIFIED BY A ROBUST QUANTITATIVE FEATURE IN THEIR GRAIN-SIZE DISTRIBUTION

H. Yizhaq[1], K. Tholen[2], L. Saban[3], T. Pähtz[4], O. Vinent Duran[5], I. Katra[3] and K. Kroy[2].
[1]Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 8499000, Israel (yiyeh@bgu.ac.il). [2]Institute for Theoretical Physics, Leipzig University, Leipzig, Germany (tholen@itp.uni-leipzig.de), (klaus.kroy@uni-leipzig.de). [3]Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, 8410501, Israel (sabal@post.bgu.ac.il), (katra@bgu.ac.il). [4]Institute of Port, Coastal and Offshore Engineering, Ocean College, Zhejiang University, 866 Yu Hang Tang Road, 310058 Hangzhou, China (tpaehtz@gmail.com). [5]Department of Ocean Engineering, Texas A&M University, College Station, TX, USA (oduranvinent@tamu.edu).

Introduction: If exposed to atmospheric flows, planetary surfaces composed of loose sand may continuously evolve into dynamic landscapes. The most common aeolian bedforms are decimeter-sized ripples and dunes ranging from tens to hundreds of meters in size on Earth and Mars. Interestingly, a whole zoo of intermediate-sized structures with meter-scale wavelength known also as large martian ripples have been discovered on Mars (Fig. 1a). Surprisingly, ripples are much larger on Mars than on Earth, reaching wavelengths on an order of 1-3 m and heights of a few cm. Smaller decimeter-long ripples can be superimposed on them (see Fig.1; [1-2]).

Currently, there is still an ongoing debate about their correct classification and formation, and they have tentatively been related to a range of aeolian and subaqueous analog bedforms on Earth [2], large impact ripples [3-5], megaripple [6; Fig.1b], and hydrodynamic ripples [7]. In this debate, it would clearly be most useful to have some clear-cut quantitative criteria to distinguish between these mesoscale bedforms.

As detailed below, we have recently found such a robust and quantitative criterion, which sets megaripples apart from all other aeolian bedforms. It is based on their non-uniform grain size distribution (GSD), which exhibits a characteristic bimodality (Fig. 2). The latter may be explained in terms of the underlying grain hopping and megaripple formation mechanism [8]. Namely, under suitable erosive conditions over a polydisperse sand bed, fine grains get more easily winnowed out by the wind, by which the coarse grains become exposed. These coarse grains are moreover kicked forward by impacts of the fine grains, even if they are not entrained into saltation, themselves. They can then accumulate at exposed sites, particularly on the megaripples' windward slopes, near the crest, which prompts the suggestive notion of an ``armoring layer'' [9].

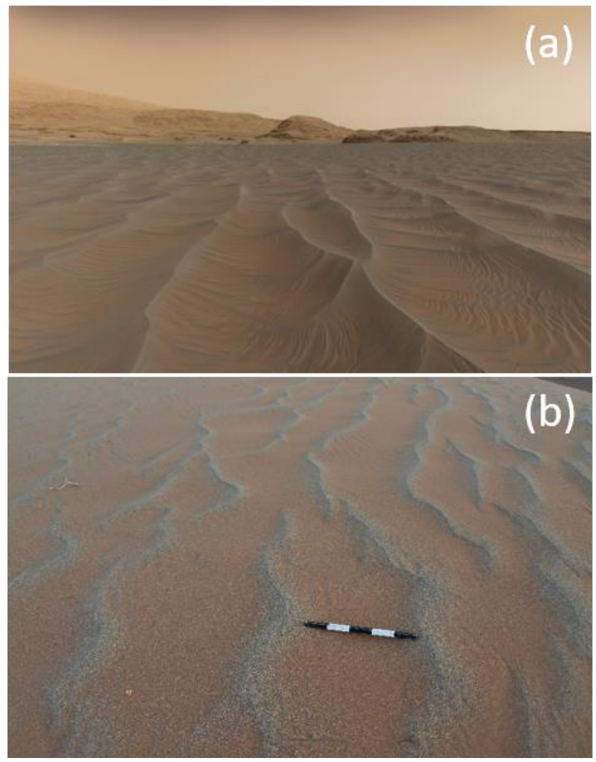

Fig. 1 (a) Multi-scale ripples on Mars as imaged by the NASA MSL Curiosity rover in Gale crater. The wavelength of the large ripples is about 1.8 m with small impact ripples between them. The amazing complexity of the bedform pattern is due to multidirectional winds and probably to different formation mechanisms. (https://an.rsl.wustl.edu/msl/mslbroser /an3.aspx). (b) Megaripples near Sossusvlei, Namibia. The scale bar is 0.5 m long. The coarse grains (grayish) accumulate at the crests and fine grains (reddish) are abundant at the troughs. Note the small ripples developed between the megaripples with $\lambda \approx 5$ cm.

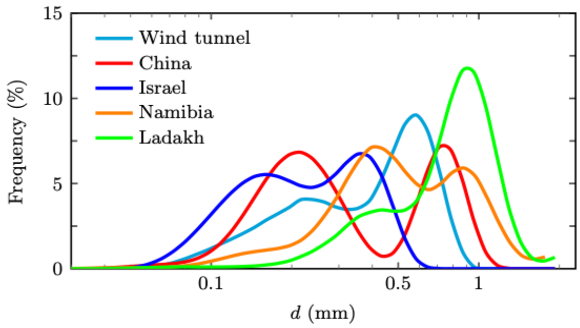

Fig. 2 Grain-size distributions (GSDs) of samples taken from megaripple crests exhibit a characteristic bimodal shape, with more or less pronounced fine-grain and coarse-grain peaks. They vary wildly as a function of sand composition and wind conditions [9].

Theory and data: A simple theoretical modelling of this sand sorting process reveals how bimodal surface GSDs emerge over time, and how they keep changing their shape under variable wind conditions [9]. The model gives a new prediction for their minimum size based on a saturation length related to the reptation length. This new scaling is ~10 times larger for martian megaripples than their terrestrial counterpart. To the wide range of possible shapes for the bimodal grain-size distributions found on megaripples corresponds a strong dispersion of their peak positions, as illustrated in Fig. 2. It thus appears that the extremely varied distributions are difficult to interpret and might have arisen from a wide variety of wind and sand conditions. Thus, they do not seem very suitable to arrive at an unambiguous criterion for classifying a sand wave as a megaripple.

Surprisingly, a kinetic model of the aeolian transport process of such bimodal sand distributions predicts a hidden invariant beneath all this bewildering complexity [8]. The model does not rely on the specific nature of the transport instability causing megaripple formation but only the following, well-established generic ingredients: (1) A bimodal sand transport mechanism, with fine-grain saltation driving coarse-grain reptation. (2) The fine-grain saltation flux is strongly under-saturated and therefore does not significantly disturb the wind speed; and (3) The surface GSDs co-evolve through winnowing of saltating fine grains and accumulation of exclusively reptating coarse grains.

On this generic basis, theory predicts a robust quantitative signature in the otherwise quite volatile megaripple GSDs, measured in the field (Fig. 2), namely, ***a fixed width of the coarse-grain peak if plotted over a logarithmic axis***, (also called its log-scale width). The main idea behind this surprising finding is illustrated in Fig. 3. Namely, one can attribute different aeolian transport regimes arising in bimodal sand to different grain sizes in the bimodal GSD. Fine grains saltate (blue), coarse grains only reptate (green) if kicked by hopping fine grains, and the coarsest grains, which are too heavy to be dislodged, do not move at all. The boundaries in the diagram are strongly wind-strength dependent, but their relation (defined by the heaviest fine grains able to barely dislodge the heaviest reptating grains) **is not**. Therefore the width is given by the ratio their diameters: the "max-size ratio" $\max(d^{(c)})/\max(d^{(f)})$. Importantly, it responds only very weakly to environmental conditions, namely between 2.75 (Earth) and 4.5 (Mars. This prediction rationalizes a large body of data (Fig 4).

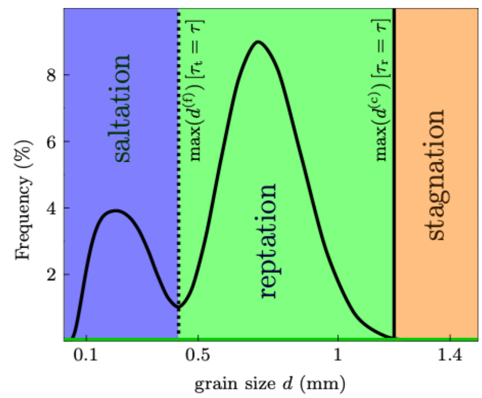

Fig. 3 A characteristic bimodal GSD and its relation to the aeolian transport modes, which constrain the logarithmic width of its coarse-grain peak [8].

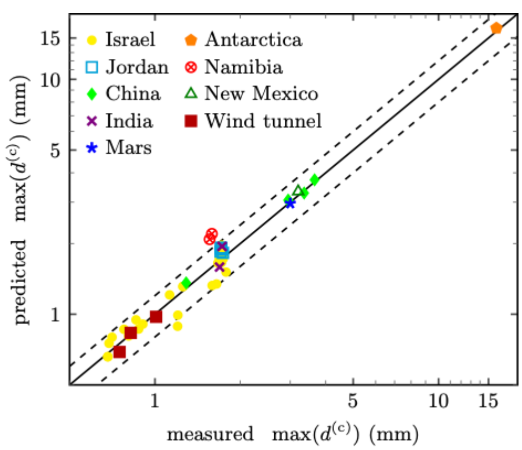

Fig. 4 For most of the measured coarsest hopping grains of diameter $\max(d^{(f)})$, and over a wide range of sands and ambient conditions, theory and data for the coarsest reptating grains of diameter $\max(d^{(c)})$ agree very well.

References: [1] Lapotre, M. G. A., et al., (2016) *Science*, 353, 6294, 55–58. [2] Lapotre, M. G. A., et al., (2021) *JGR Planets*, 126, e2020JE006729. [3] Lorenz, R., (2020) *JGR Planets* 125, doi:10.1029/2020JE006658. [4] Sullivan et al., (2020) *JGR Planets* v. 125 no. e2020JE006485. [5] Yizhaq et al., (2021) *JGR Planets* 126, e2020JE006515. [6] Gough et al., (2021) *JGR Planets* 10.1029/2021JE007011. [7] Vinent Duran, O. et al., (2019) *Nat. Geoscience*, 12(5), 345–350. [8] Tholen, K. et al., (2022) *Nat. Comm* 13(1), 162, https://doi.org/10.1038/s41467-021-26985-3. [9] Lämmel, M. et al., (2019) *Nat. Phys.* 14, 759–765.