Rediscovery of the fluid drag ripples in wind tunnel experiments

H. Yizhaq[1], N. Swet[2], L. Saban[3] and I. Katra[4], [1]Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 8499000, Israel (yiyeh@bgu.ac.il). [2]Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, 8410501, Israel, (swet@post.bgu.ac.il). [3]Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, 8410501, Israel (sabal@post.bgu.ac.il). [6] (katra@bgu.ac.il).

Introduction: Aeolian impact ripples are abundant in arid regions on Earth and on the surface of Mars. They develop from the instability of an initially flat bed of cohesionless sand that is mobilized into saltation by wind shear stress. Impact ripples in relatively fine desert sands typically have unimodal grain size distributions, with coarser-than-average grains concentrated at ripple crests (e.g., [1-2]). On Earth, ordinary impact ripple wavelengths typically are < 30 cm and heights less than 1 cm [3]. However, on Mars, ripple-like bedforms with crests lacking very coarse grains can be much larger both in wavelength and height [4-6]. Two size modes of these ripples were observed: small (decimeter scale) ripples similar to impact ripples that commonly cover dune surfaces on Earth [7-8] and large, meter scale ripples that have no corresponding terrestrial analog [11]. It is important to note that these very large martian ripples do not have crests covered with very coarse grains, so are not like terrestrial megaripples and their size is much smaller than martain megaripples. Based on data sent by the NASA Mars Science Laboratory (MSL) rover in Gale Crater, Lapotre et al. [5-6] gave an alternative hypothesis for the origin of the large ripples that superimpose dune surfaces at the MSL landing site [11]. According to their theory, the large ripples are fluid drag ripples which are similar in their morphology to subaqueous ripples. Reasons for this interpretation include: (1) the atmosphere on Mars has a higher kinematic viscosity than on Earth; (2) sinuous crest lines of the martian very large ripples are morphologically similar to subaqueous bedforms on Earth whereas terrestrial impact ripples are straight; and (3) measurements of ripple wavelengths reveal a meter-scale mode that is distinct from smaller impact ripple wavelengths, implying a separate formative mechanism [6] analogous to subaqueous current ripples which form in unidirectional water streams on Earth. According to Lapotre et al. [6], large martian ripples are a class of bedform distinct from impact ripples. Since Bagnold's seminal work in the wind tunnel with very fine sand [1], this experiment has not been repeated and a deep understanding of the formation of aeolian fluid drag ripples is lacking. Recently, a candidate of aeolian drag ripples (also known as aerodynamic ripples) with $\lambda = 15-20$ cm in unimodal sand was observed in the field [6], but no information was given for the grain size distribution. It is also not known, what are the conditions necessary for the coexistence of the two-scale ripples.

Here, at the first time, we perform a targeted experiment on the formation of fluid drag ripples, using a boundary layer wind tunnel [10] with sand of 40-70 µm.

Theoretical considerations: Coexistence of small and large active ripples composed of fine unimodal sand is rarely found on Earth ([9], Figs. 1E and F). Bagnold ([1], p. 161) observed in a wind tunnel experiment with very fine sand (modal diameter of 80 µm) an abrupt transition between small impact ripples ($\lambda \approx 1.5$ cm) to larger fluid drag ripples ($\lambda \approx 20$ cm) when the wind velocity exceeded $u_* = 0.3$ m/s. Greeley and Iversen ([12], p.155) also reported the occurrence of fluid drag ripples ($\lambda \approx 8.5$ cm) with 30 µm glass beads. They argued that the geometry of these ripples is determined by local variations in the surface shear stress rather than by ballistic impacts, and emphasized the role of grains transported in suspension. The suspension load is characteristic of wind friction speeds exceeding the grain terminal fall speed so that most of the grains move in suspension or modified saltation, and the impact splash mechanism on the bed is less dominant as for usual saltation. These early experiments indicate that fluid drag ripples can be formed on Earth with very fine sand and above the fluid threshold of the fine sand. Fig. 1 presents analysis of the conditions where fluid drag ripples might form.

The fluid drag ripples of Bagnold's experiment formed above wind speeds that would flatten the small impact ripples (2-3 times u_{*t}, [13]) and in the vicinity of the suspension threshold ($u_* = W_s$ where W_s is the settling velocity). The Stokes settling velocity is given by $W_s = (\rho_s - \rho_f) g D^2 / 18\mu$ [13] where μ is the dynamic viscosity, ρ_f is the fluid density and D is the grain diameter. Farrell and Sherman [14] gave a more accurate formula for the settling velocity on Earth $W_s = 4.248D + 0.174$ where D is given in mm. Note that the settling velocity is a complicated parameter for which no simple formula applies across all particle sizes and conditions; uncertainties exist, and in any case, the transition from saltation to suspension is gradual.

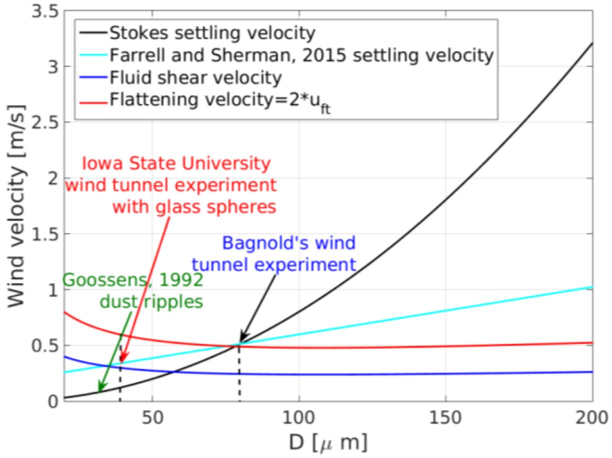

Fig. 1 According to very limited understanding from the very few experiments conducted decades ago, aeolian fluid drag ripples are most likely to develop at the transition between saltation and suspension. The fluid drag ripples can form above or near the suspension threshold $W_s = u_*$ where W_s is the settling velocity (the cyan curve according to [14]). This analysis seems consistent with Bagnold's preliminary experiment using 80 µm sand grains.

Although the analysis (Fig.1) is only an approximation, it nicely explains Bagnold's experiment when the fluid drag ripples formed after the impact ripples flattened.

Results: Our wind tunnel experiment shows that small impact ripples started to develop at wind speed of 3.6 m/s and continue to grow ($\lambda = 0.7$ cm) with increasing wind speed. These small impact ripples have been flattened under wind speed of 6 m/s. The larger fluid drag ripples started to develop at wind speed of 5 m/s. Their wavelength increased with wind speed, and their sinuosity strengthened as they became discontinues like subaqueous ripples. Small avalanches have been observed when local slopes exceeded the angle of repose (Fig.2a). Decreasing the wind speed again to 4 m/s allowed the impact ripples to develop atop and between the fluid drag ripples as shown in Fig. 2b. The fluid drag ripples flattened at wind speed of approximately 9.5 m/s. The experimental results are in agreement with the theoretical framework presented in Fig.1 – the two types of ripples can coexist at certain range of low wind speeds.

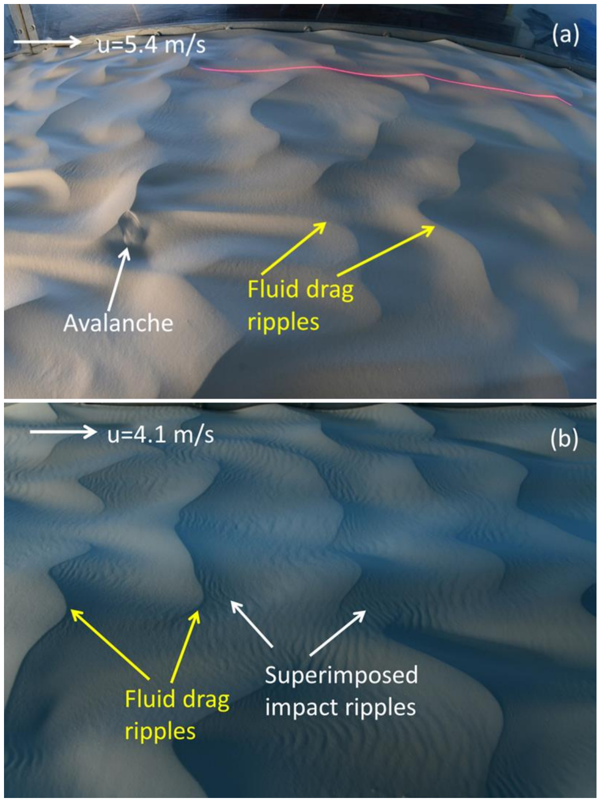

Fig. 2 (a) A small avalanche during the development of the fluid drag ripples at wind speed of 5.4 m/s. (b) Coexistence of impact ripples ($\lambda \approx 0.7$ cm) and larger wavy fluid drag ripples ($\lambda \approx 12$ cm). The fluid drag ripples formed at wind velocity of 7.7 m/s and then wind speed was lowered to 4.1 m/s to allow the development of the small impact ripples.

References: [1] Bagnold, R. A. (1941) Methuen, London. [2] Greeley, R. and J. D. Iversen (1985). [3] Sharp R. P. (1963) *J. of Geology*, 71, 617-636. [4] Sullivan, R. et al., (2008) *J. Geophys. Res.*, 113, E06S07. [5] Lapotre, M. G. A., et al., (2016) *Science*, 353, 6294, 55–58. [6] M. G. A., et al., (2018) Geophysical Research Letters, 45, 10, 229-239. [7] Sullivan, R. et al., (2005) *Nature*, 436, doi:10.1038/nature03641. [8] Yizhaq, H. et al., (2014) *Icarus* 230, 143-150. [9] Wilson. I. G. (1972) *Sedimentology*, 19, 173-210. [10] Schmerler, E. et al., (2016) *Aeolian Research*, 22, 37-46. [11] Ewing et al., (2017) *J. Geophys. Res. Planets*, 122, 2544–2573. [12] Greeley, R., and Iversen, J. D. (1985) Cambridge Univ. Press, New York. [13] Pye, K. and Tsoar, H., (2009) Springer-Verlag Berlin Heidelberg. [14] Farrell, E. J. and Sherman D. J. (2015) *Progress in Physical Geography*, 39, 361-387.