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Longevity of aeolian megaripples

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ABSTRACT

Megaripples are distinguished from regular ripples by their larger dimensions and bimodal grain-size distributions. The interplay between wind, grain size and ripple morphology (height and wavelength) controls their development. Two main mechanisms limit megaripple height. The first, megaripple flattening due to winds that are above the fluid threshold of the coarse grains, destroys the armoring layer of the megaripple. The second is megaripple erosion by the impacts of fast-moving, fine saltating grains that propel the coarse grains constituting the armoring layer. For any given wind regime and grain size distribution, the potential megaripple dimensions are limited by these two mechanisms. Here we study the first mechanism and estimate the duration of strong winds (sustained above the fluid threshold) needed to flatten megaripples. Strong gusts of wind, in contrast, cannot destroy the megaripples but can cause ripple migration. Based on data from previous works on megaripples, we find a scaling law between the ripple morphology and the coarse mode of grains at the crest. Using this scaling relation allows us to calculate the wind velocity and duration needed for megaripple flattening. In general, the coarser the particles at the megaripple crest, the stronger the wind needed to flatten the megaripples. Moreover, the greater the strength of the wind required to flatten the megaripples, the lower the recurrence probability. Taken together, these findings increase the longevity of megaripples. We apply the results for a megaripple field in the southern Arava valley (Israel).

1. Introduction

Aeolian megaripples are large ripples that form when grain-size distribution is bimodal (Bagnold, 1941; Sharp, 1963; Ellwood et al., 1975; Zimbelman et al., 2009; Yizhaq et al., 2012a; Warren, 2014; Lorenz and Zimbelman, 2014). The coarser particles of this bimodal regime cover the megaripple crest and form a protective layer that prevents ripple erosion by the wind and that allows the ripple to grow further in height and wavelength (Yizhaq et al., 2012b) (see Table 1). Movement of the coarse grains is via creep and reptation due to the impingement of incoming saltating fine particles. Whereas small, so-called normal ripples can form in minutes, the growth of megaripples is a much slower process that for very large megaripples can take years, decades or even centuries (Bagnold, 1941; Milana et al., 2010). According to Bagnold (1941), the difference between normal ripples and megaripples is that the former cease to grow at some point whereas megaripples can grow indefinitely simply because the wind is too weak to carry away the coarse grains at the crest of the megaripple. However, it has also been shown that there are mechanisms that limit megaripple growth (Katra et al., 2014) and that megaripples can be destroyed by very strong winds.

Among the growth-limiting mechanisms affecting megaripples, flattening occurs when wind velocity exceeds the fluid threshold of the coarse particles constituting the armoring layer at the megaripple crest (Isenberg et al., 2011; Katra et al., 2014). But the criterion of wind velocity alone is insufficient to explain flattening because the armoring layer of a given megaripple comprises a finite volume of coarse particles. Therefore, in addition to its velocity, there is also the length of time the wind must blow above the fluid threshold – or once saltation has started, above the impact threshold – to completely erode the armoring layer (impact threshold on Earth is ∼0.8 times the fluid threshold velocity; Kok et al., 2012). Thus, high wind speed events of short duration (gusts) will only cause megaripple migration but not its destruction.

The aim of this work was to develop a general criterion for the longevity of megaripples based on the coarse mode of the grain-size distribution at the crest and on the wind statistics at the megaripples site. First, we used published data on megaripples

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Table 1
Megaripple characteristics in previous works.

Location	Wavelength (cm)	Height (cm)	RI (Ripple Index)	Typical size of crest coarse grain (cm)	Reference
China's Kumtagh Desert	31	1.5	20.7	–	Qian et al., 2012
Northern Sinai, Egypt	40	–	–	0.071	Tsoar, 1990
Askja region northeast Iceland	48	7	6.9	0.075 stoss slope	Mountney and Russell, 2004
Nahal Kasuy, Israel	70	5	14	0.1	Isenberg et al., 2011
Kelso dunes, CA, U.S	84	5.5	15.3	0.125	Sharp, 1963
White Sands, NM, U.S.	100	1	100	0.2	Jerolmack et al., 2006
Southern San Joaquin Valley in California	186	18	10.3	–	Sakamoto-Arnold, 1981
Askja region, northeast Iceland	215	18	11.9	0.3 stoss slope	Mountney and Russell, 2004
Wadi Rum, Jordan	217	20	10.9	0.2	Yizhaq et al., 2009
GSDNPP central Colorado	280	19	14.7	–	Zimbelman et al., 2009
Coachella Valley, CA, U.S.	304	30	10.1	0.4	Sharp, 1963
Askja region, northeast Iceland	320	30	10.7	–	Mountney and Russell, 2004
Wright Valley, Antarctica	320	9	35.6	0.96	Lancaster et al., 2002
Victoria Valley, Antarctica	350	15	23.3	–	Selby et al., 1974
GDNPP central Colorado	370	25	14.8	0.8	Williams et al., 2002; Wilson et al., 2003
Southern San Joaquin Valley in California	472	23.7	19.9	–	Sakamoto-Arnold, 1981
Edwards Canada	970	60	16.2	1	Williams et al., 2002
Libyan Desert, Egypt	2000	60	33.3	–	Bagnold, 1941
Puruya and Carachi Pampa	3500	100	35	2.3	Milana, 2009
Puruya and Carachi Pampa	4400	230	19.1	2.5	Milana, 2009

to find a scaling law between megaripple height and wavelength to the coarse particle mode. This scaling law used to update the threshold wind velocity condition needed for megaripple flattening (Katra et al., 2014). Then, the time needed for the erosion of the armoring layer calculated for megaripples at the Qetura sand in Arava Valley, Israel (29°57′54″N, 35°4′44″E). The calculated time and the wind velocity statistics allow the estimation on the longevity of the megaripples at the site. In principle, this procedure can be applied at any megaripple site.

1.1. Scaling laws for megaripples

Several studies have shown a correlation between megaripple wavelength and the maximum particle size at the megaripple crest (Stone and Summers, 1972; Tsoar, 1990; see Figs. 3 and 4 in Williams et al., 2002; Milana, 2009; Pelletier, 2009). For example, Stone and Summers (1972) suggested that this relationship can be described by $\lambda = 63.8D^{0.75}$, where D (mm) is the average diameter of the sand grains on the ripple crests and λ (cm) is the wavelength. These studies found that the larger the grain size, the larger the wavelength, although the exact functional dependence between the studies varies. Fig. 1 shows the results based on field data from various locations (Table 1). The ripple index (*RI*), which is the slope of the linear regression of the wavelength vs. the height, is $RI = 21.97$. This value is reasonably consistent with the value of 15 that was published by Sharp (1963). For megaripples with wavelengths up to 3 m, the relation between the wavelength and grain coarse mode can be approximated by a linear fit ($\lambda = 749D_c$), in which both λ and the coarse mode diameter D_c are in cm. For larger wavelengths (gravel megaripples), the best fit becomes quadratic ($\lambda = AD_c^2 + BD_c$), where $A = 670$ cm^{-1} and $B = 40.7$ are the regression coefficients.

For simplicity, we use the linear regression, which gives good results for megaripples covered by coarse grains with diameters up to 4 mm. This scaling law was therefore used to derive an expression for the wind velocity needed, as a function of the coarse grain diameter D_c, to cause megaripple flattening.

2. Fluid threshold velocity for megaripples flattening

Here we follow the calculation presented in Katra et al. (2014) for the threshold wind velocity needed to flatten megaripples. The fluid threshold velocity u_t at height z above the bed is:

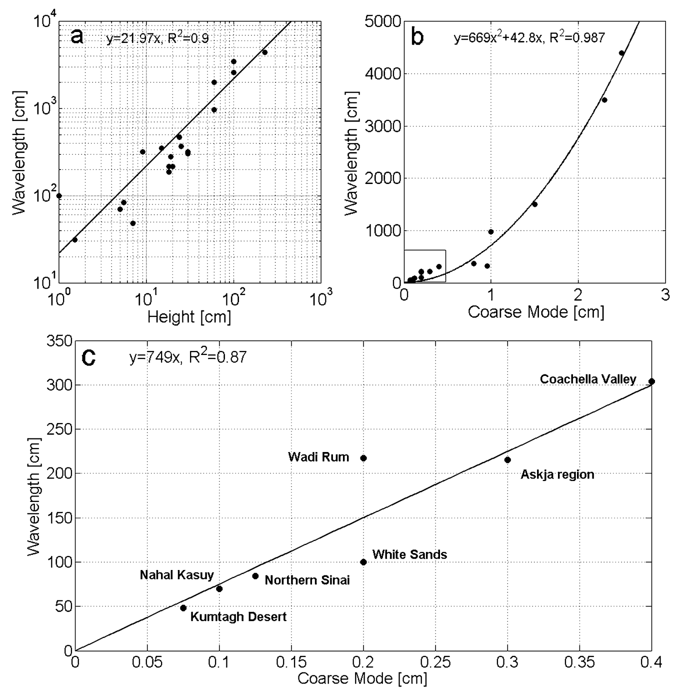

Fig. 1. Megaripple morphometry relations based on previous work (see Table 1). (a) Wavelength vs. height (the slope is the ripple index, *RI*). (b) Wavelength as a function of the coarse mode of samples taken from the crests. The best fit is quadratic, but for wavelengths up to 3 m, the relation is linear (c).

$$u_t = \frac{1}{\kappa} A (\sigma g D_c)^{0.5} \ln(z/z_e) \tag{1}$$

where $\kappa = 0.4$ is the von Karman constant, $A = 0.1$, and $g = 9.8$ m/s^2 is the acceleration due to gravity. In addition, $\sigma = (\rho_p - \rho_a)/\rho_a$, where ρ_p is the particle density and ρ_a is the air density. z_e, which is the surface roughness modified by the effects of both saltation flux and ripples topography defined by

$$z_e = z_s \exp\left[\frac{1}{2}\left(\delta \ln\left(\frac{L}{z_s}\right)\right)^2\right] \tag{2}$$

where L is the half width of the ripple at half height, δ is the maximum slope of the ripple ($\approx h/L$), and z_s is the modified surface roughness in the presence of saltation only:

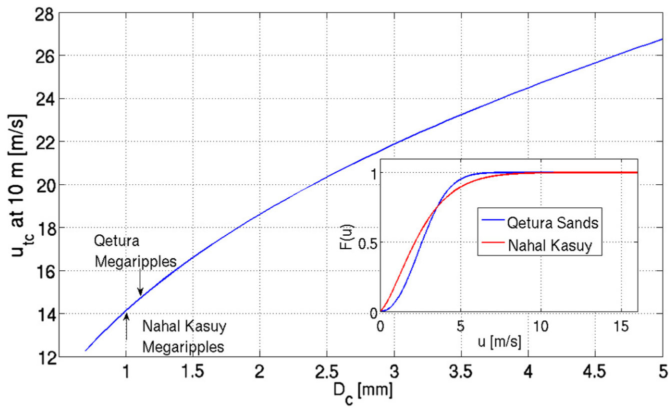

Fig. 2. The calculated threshold velocity needed for megaripple flattening as a function of the coarse grain mode diameter (D_c). The inset shows the cumulative probability function (based on the calculated Weibull distribution) $F(U) = 1 - \exp[-(\frac{U}{c})^k]$ (Manwell et al., 2009) for the Nahal Kasuy and the Qetura sands located in the southern Negev desert in Israel.

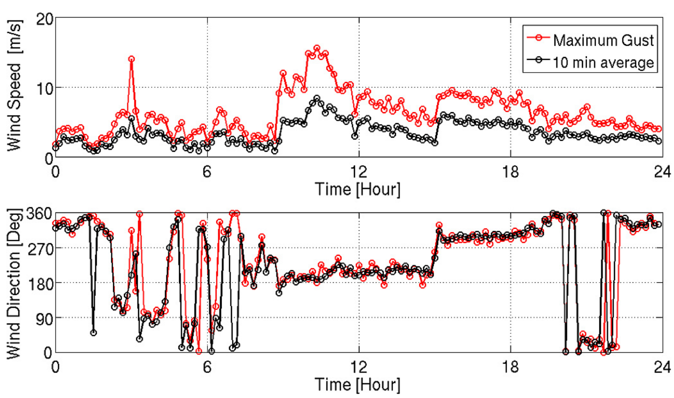

Fig. 3. Wind speeds (maximum gusts in red and 10-min averages in black) during the storm of April 20, 2014 measured at Yotveta metrological station (8 km south of Qetura megaripples field). The lower panel shows the wind direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$z_s = \frac{D_c}{15} + c_m \frac{(u_* - u_{*t})^2}{g} \tag{3}$$

where D_c is the grain diameter and $c_m = 0.132$ for field conditions (Sherman and Farrell, 2008). Assuming that $h \ll L$, L can be approximated by $L \approx \frac{\lambda}{4}$, thus, $\delta \approx \frac{4h}{\lambda} = \frac{4}{RI}$, where RI is the ripple index which is the ratio of megaripple wavelength to height. To find a general dependence of the threshold velocity u_t, we need to use the scaling law between the megaripple wavelength and the coarse mode of the grains at the ripple crest via the linear equation $\lambda = 749D_c$ (see Fig. 1c) and the value for ripple index ($RI = 21.97$). Fig. 2 shows u_t as a function of the coarse grain diameter D_c at a height of 10 m (the standard measurement height of meteorological stations). It is important to note that the calculated graph takes into account the megaripple dimensions and the size of the coarse grains at the crest. It can be clearly seen that the coarser the armoring layer, the stronger the wind needed to flatten the megaripple.

From this fluid threshold analysis, however, one cannot infer whether the megaripples in Qetura will be flattened because the wind can exceed u_{tc} for only short durations (gusts), which may not be enough to erode the armoring layer. Under such conditions, the megaripple will migrate downwind. Fig. 3 shows the wind speed over time during a wind storm on April 20, 2014, which was recorded at a meteorological station near Qetura. Although the maximum 10-min average wind speed was 10 m/s, the maximum gust wind speed exceeded 15 m/s, which is above the calculated fluid threshold velocity for coarse particles $u_{tc} = 14.66$ m/s for the megaripples at the Qetura site (Fig. 2). Despite the presence of wind that exceeded the fluid threshold velocity, however, this and a later storm on April 25 only affected downwind megaripple migration, the distance of which was proportional to megaripple height (Fig. 4) as also observed by Lorenz and Valdez (2011).

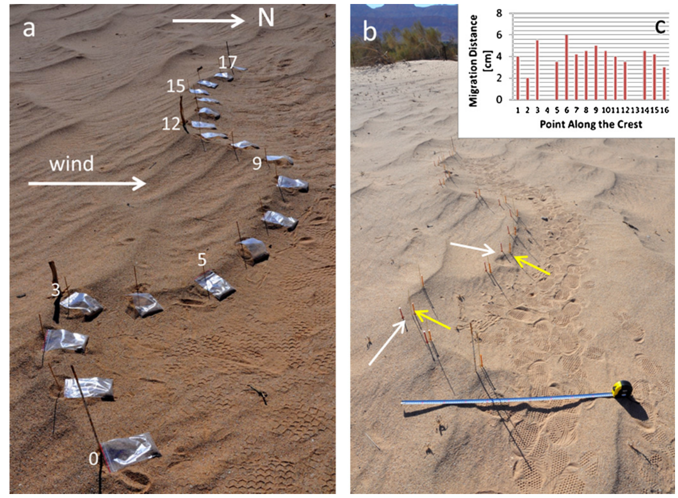

Fig. 4. (a) A long megaripple at Qetura on 22.7.13. The distance along the crest between two successive plastic bags is 30 cm; (b) the same megaripple on 30/4/14. The iron pegs indicated the advance of the crest during this period which occurs only in April due to two storms. The arrows indicate the location before (white) and after the storm (yellow) for two locations along the crest. The migration distance of each point is shown in the inset (c). The lowest point along the crest (6) moved 6 cm, whereas the highest point (11) moved only 4 cm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The above derivation is based on the assumption that the wind was perpendicular to megaripple alignment during this period (at Qetura, the megaripple crests are in a west–east direction). For winds that are not perpendicular to the crests, more time will be needed to flatten the megaripples as part of the wind energy will be used to change the plane geometry of the megaripple field, including breaking the crests into short segments and altering crest orientation (Yizhaq et al., 2012a).

2.1. Time needed for megaripples flattening

To predict the time needed for megaripple flattening, first the time required for the wind to erode the armoring layer of megaripple crests must be estimated. Coarse layer removal will cause the disappearance of the megaripples and their replacement by normal ripples (see Fig. 12 in Isenberg et al., 2011). We performed this calculation for the megaripples at the Qetura sands (Fig. 4), where the depth of the coarse grain layer is about 0.1 m and its width is about 0.2 m. Thus, the volume V of coarse sands along 1 m of the crest can be estimated as the volume of a triangular prism and its mass as $m = V(1-p)\rho$, where $p = 0.35$ is the sand porosity and $\rho = 2650$ kg/m^3 is the density of a quartz grain. Using the Lettau equation for sand flux (Lettau and Lettau, 1978),

$$Q = C_L \sqrt{\frac{D_c}{D_{250}}} \frac{\rho_a}{g} u_*^3 \left(1 - \frac{u_{it}}{u_*}\right) \tag{4}$$

$C_L = 6.7$, D_c is the coarse grain diameter (in meters), D_{250} is a standard sand dune grain diameter ($250 \cdot 10^{-6}$ m), and $u_{it} \approx 0.8u_* = 11.73$ m/s is the impact wind velocity. The time needed to erode one meter is Q/m. Using Bagnold's expression for fluid threshold velocity, $u_* = A\sqrt{gD_c\sigma}$ in Eq. (4), where $\sigma = (\rho_p - \rho_a)/\rho_a$ and the calculated coarse particles mass m, gives

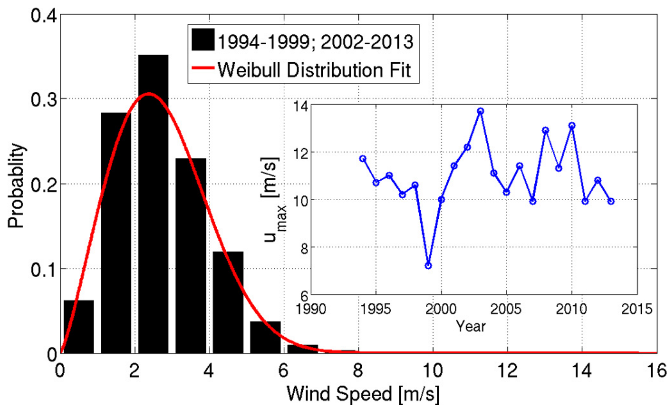

Fig. 5. Wind probability density function for the years 1994–1999 and 2002–2013 measured at the nearby Yotveta metrological station (for the missing years, the data were hourly averaged) and the Weibull approximation (Lorenz et al., 1995; Manwell et al., 2009) $p(U) = (\frac{k}{c})(\frac{U}{c})^{k-1}\exp[-(\frac{U}{c})^k]$, where U is the wind speed, k is the shape factor, and c is the scale factor. The latter two parameters are functions of average wind speed ($\bar{U}$) and standard deviation (σ_U) that can be approximated by Manwell et al. (2009) as $2.268 = (\frac{\sigma_U}{\bar{U}})^{-1.086}$; $3.065 = \bar{U}(0.568 + 0.433/k)^{-1/k}$. The inset shows the maximum speed for each year (10-min average). The maximum wind event occurred on March 18, 2003 when the wind speed was 13.7 m/s.

$t_{\text{flattening}} = 516$ s, which works out to 8.6 min to erode one meter. It is important to note that this result is only an approximation. Moreover, it is probably the lower limit for $t_{\text{flattening}}$, as we assume here that the wind direction is constant and that the impact mechanism is operating immediately with no time lag. In addition, the estimation of u_t in the above derivation is based on the assumption of a certain height. In the course of megaripple destruction, however, megaripple height decreases and the crests may be masked by a saltation layer, which means that a higher u_t will be needed to lift the coarse particles. Based on 10-min average measurements, the winds at Qetura exceeded u_t three times (18.3.2003; 8.5.2008; 28.2.2010) during 20 yrs of recorded wind data (see Fig. 5). The wind speed data (gusts and 10 min average) for the three extreme wind events are shown in the supplementary material. In all of events, the wind was from the west, parallel with the crest-lines, and therefore, it was probably insufficient to cause megaripple flattening. Thus, the estimated longevity of the Qetura megaripples is at least 20 yrs. We have documented the megaripples at this site since 2009, at which time they were already developed.

Megaripples at Nahal Kasuy (29°59′14″N, 34°4′25″E) that had smaller dimensions than those at Qetura (indicated in Fig. 2) were flattened by a series of wind storms in February 2009 when the average wind speed exceeded 15 m/s (10-min average, Isenberg et al., 2011).

3. Discussion and conclusions

As was done for the Qetura megaripples, similar estimations can be performed for megaripples at different sites where the depth and width of the armoring layer are known. This study has provided general insight into megaripple longevity. As such, megaripples covered with very coarse particles with diameters in the 3–4-mm range will only be flattened by extremely rare events with very strong winds ($\gtrsim$22 m/s), and therefore, they can endure for very long periods. For example, the age of the largest megaripples on Earth, located on the Puna Plateau (de Silva et al., 2013), was estimated using the optically stimulated luminescence (OSL) dating technique to be 1730 ± 130 yrs (Milana et al., 2010). Of huge dimensions, these megaripples will probably remain intact for a very long time because the coarse particles forming their armoring layer cannot saltate. Using extreme wind statistics like Gumbel distribution (Manwell et al., 2009), based on field measurements of extremes, can help to estimate the recurrence period of the extreme wind (10-min average) and thus the prediction of the longevity of megaripples at specific locations, if the prediction is based on the assumption that the extreme wind is perpendicular to the crests orientation. Megaripple flattening can also be a result of a series of strong winds blowing from the same direction (see Isenberg et al., 2011; Yizhaq et al., 2012a). In this case, the cumulative effect of the storms is the erosion of the armoring layer. By these arguments, the dimensions of megaripples for specific locations can give information about the wind extreme wind events. Their existence means that the wind was below u_t and its blowing time below $t_{\text{flattening}}$ for this specific megaripples.

Megaripples of varying sizes have been documented on Mars (Lorenz and Zimbelman, 2014). The scaling laws between wavelength, height, and coarse mode on Mars, however, are not known. Using the same terrestrial scaling laws strictly for illustration purposes gives $u_{tc} = 72$ m/s for megaripples of the same size as those at Qetura, but such strong winds are rarely observed on Mars (Lorenz and Zimbelman, 2014).

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.04.004. These data include the Google map of the most important areas described in this article.

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