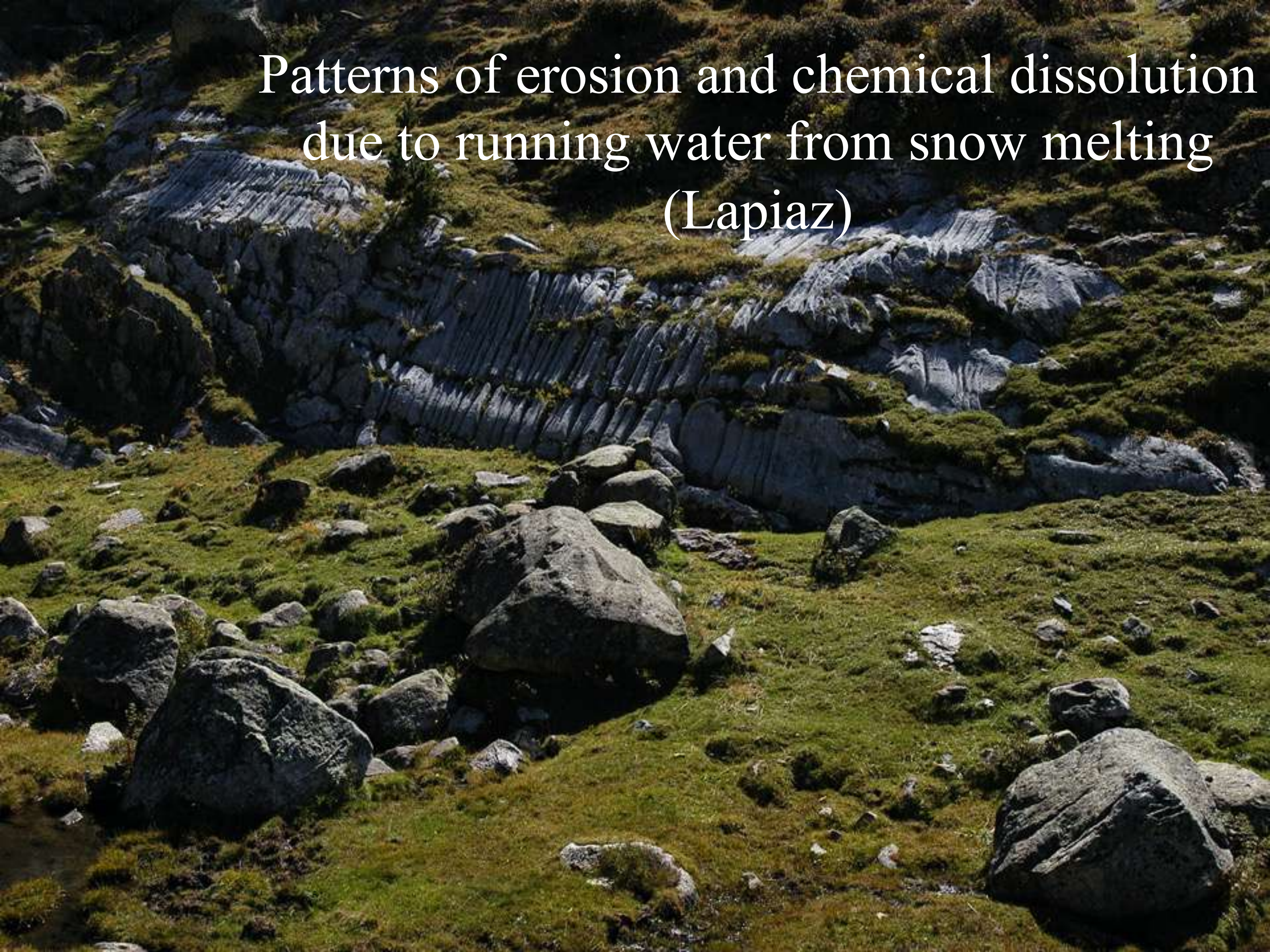
Patterns in Geomorphology

Antonello Provenzale
IGG CNR, Italy

Hezi Yizhaq
BIDR, Ben Gurion University, Israel

Patterns of erosion and chemical dissolution due to running water from snow melting (Lapiaz)



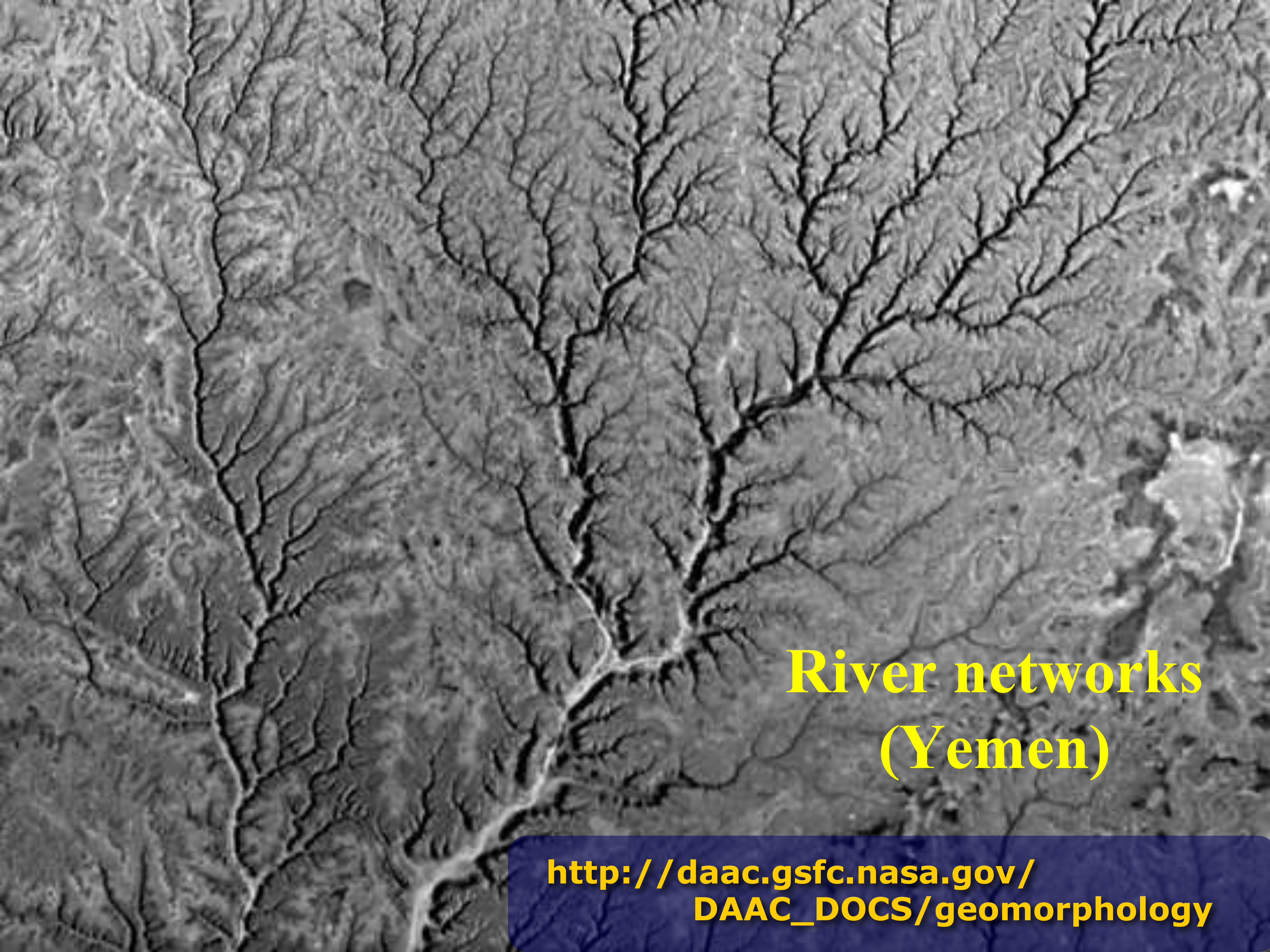
Patterns of erosion and chemical dissolution

Erosion patterns in badlands (Tzin valley, Israel)

Patterns of erosion and deposition: Meandering rivers (Ucayali river, Peru)

http://daac.gsfc.nasa.gov/ DAAC_DOCS/geomorphology

Patterns of erosion and deposition: Braided rivers



River networks (Yemen)

http://daac.gsfc.nasa.gov/
DAAC_DOCS/geomorphology

Coastal patterns (coast of Carolina, USA)

Courtesy of A. Brad Murray

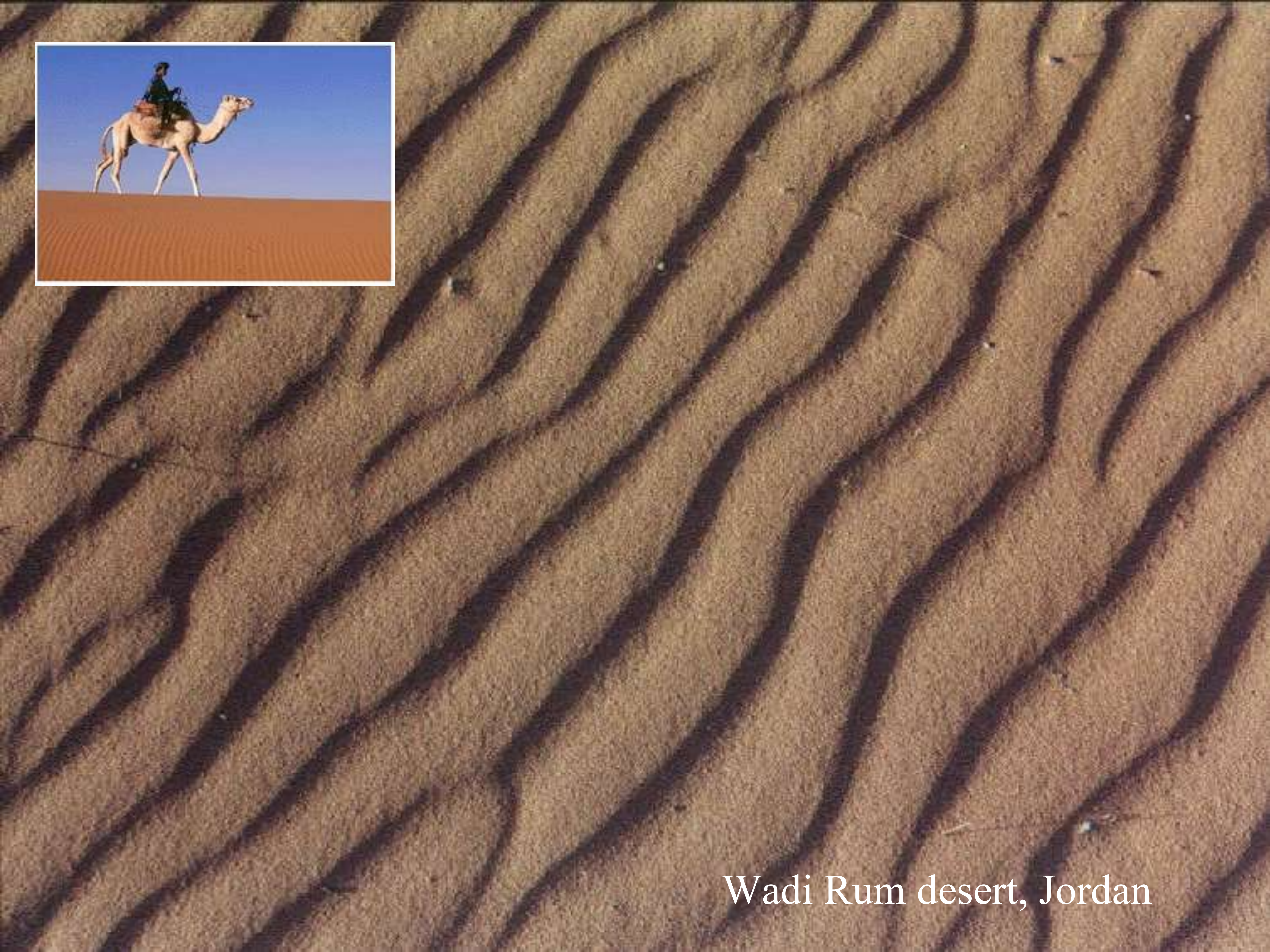
Aeolian patterns
Great Sand Dunes National Monument, Colorado,
photo by Bob Bauer

Aeolian bedforms
in deserts and sandy beaches:

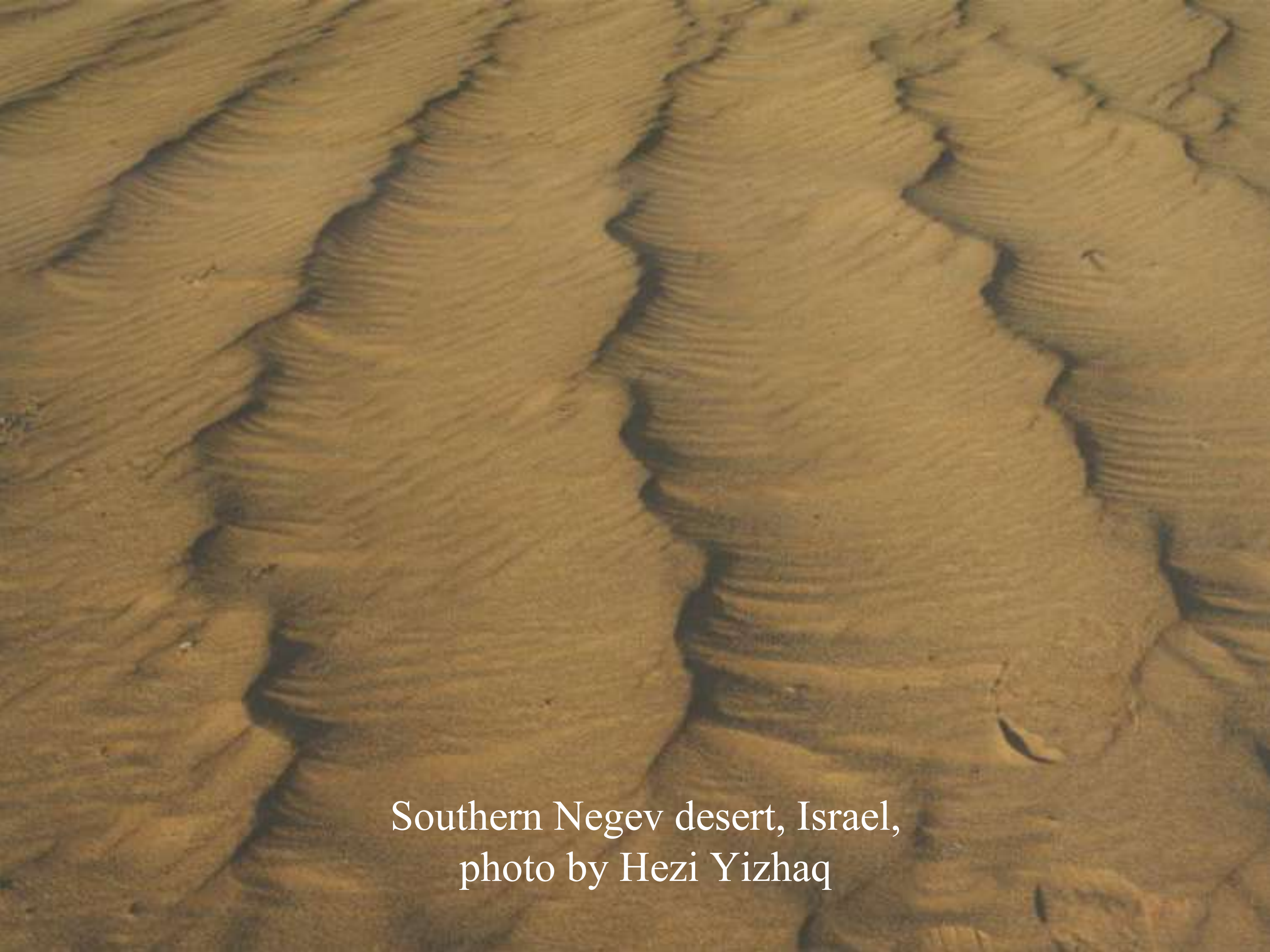
Ripples
(length of cm, amplitude of mm)

Megaripples
(length of meters, amplitude of cm)

Dunes
(length of tens or hundreds of meters,
amplitude of (tens of) meters)



Wadi Rum desert, Jordan



Southern Negev desert, Israel,
photo by Hezi Yizhaq

Types of (non-vegetated) dunes:

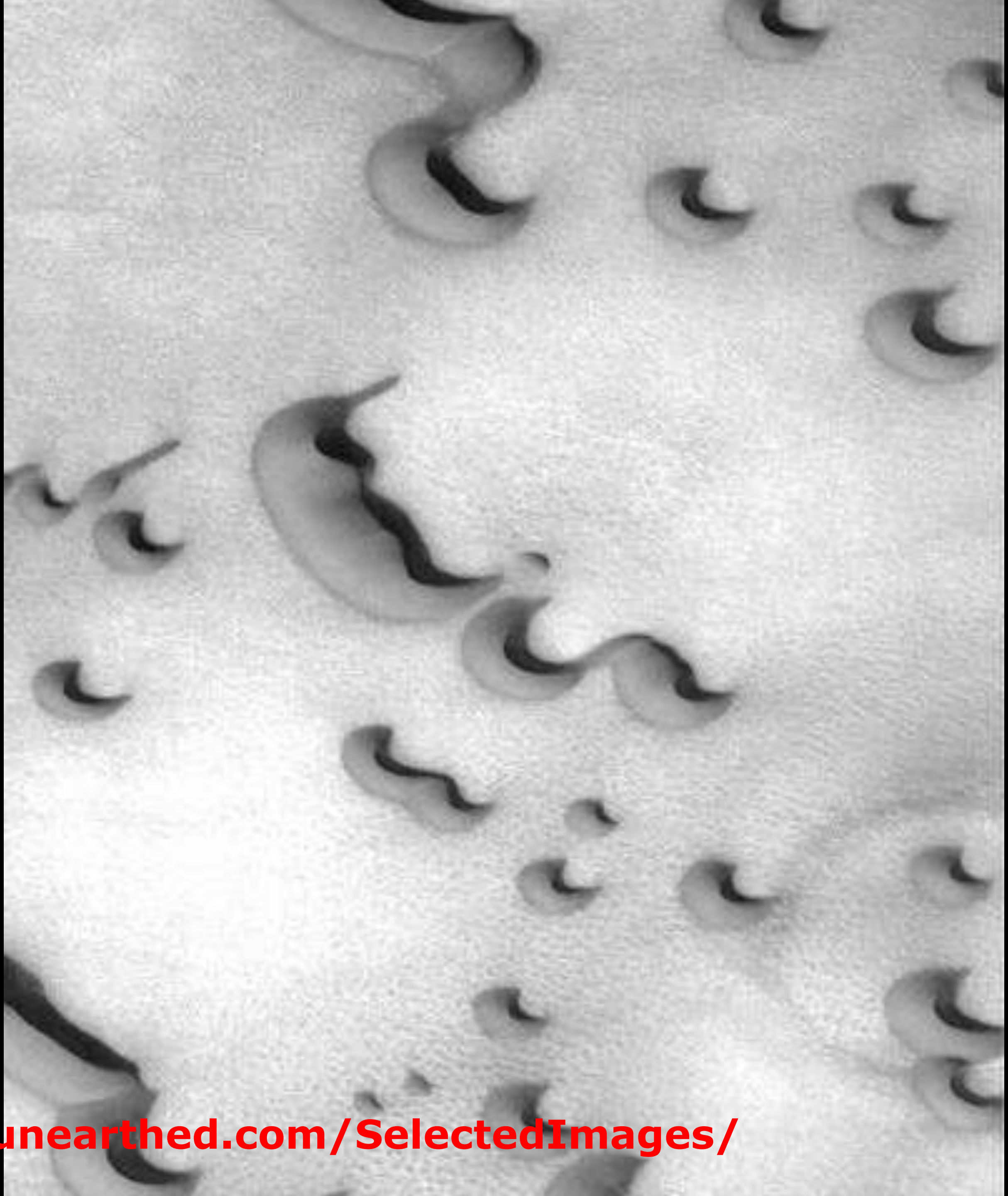
Barchans

Transverse

Seif (linear) dunes

Star dunes

Barchan dunes on Mars



http://www.marsunearthed.com/SelectedImages/

Namib desert

http://daac.gsfc.nasa.gov/DAAC_DOCS/geomorphology

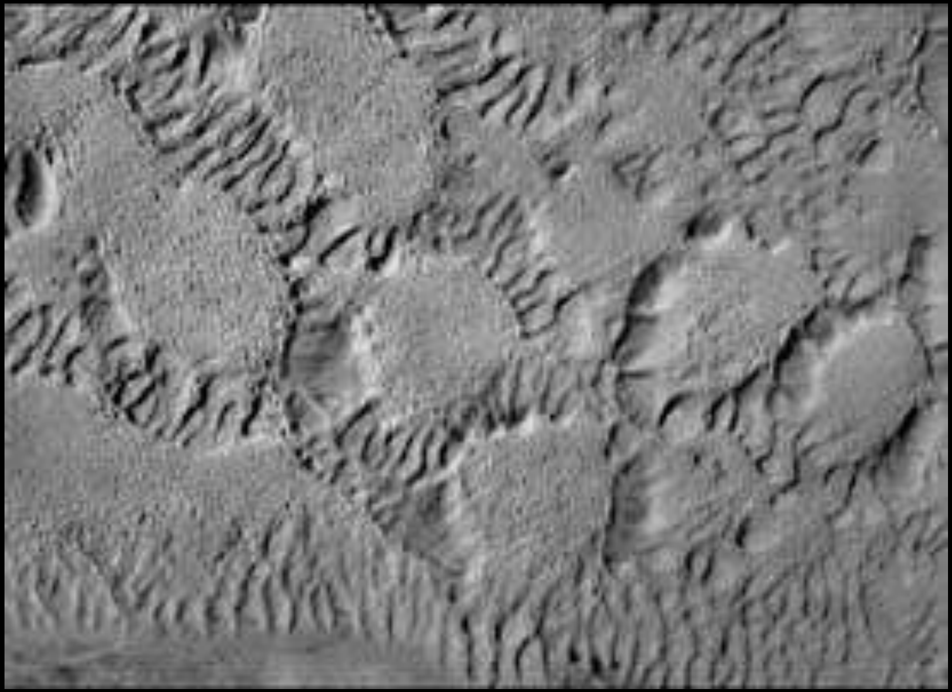
Linear dunes, Mauritania

http://daac.gsfc.nasa.gov/
DAAC_DOCS/geomorphology

Namib sand sea

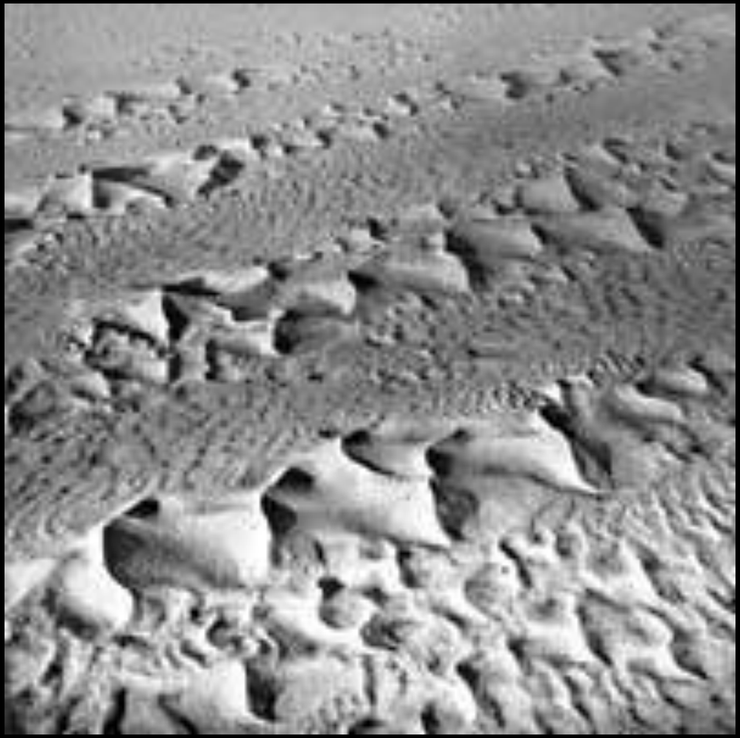
http://daac.gsfc.nasa.gov/DAAC_DOCS/geomorphology

Complex dune structures (Saudi Arabia)



http://daac.gsfc.nasa.gov/DAAC_DOCS/geomorphology

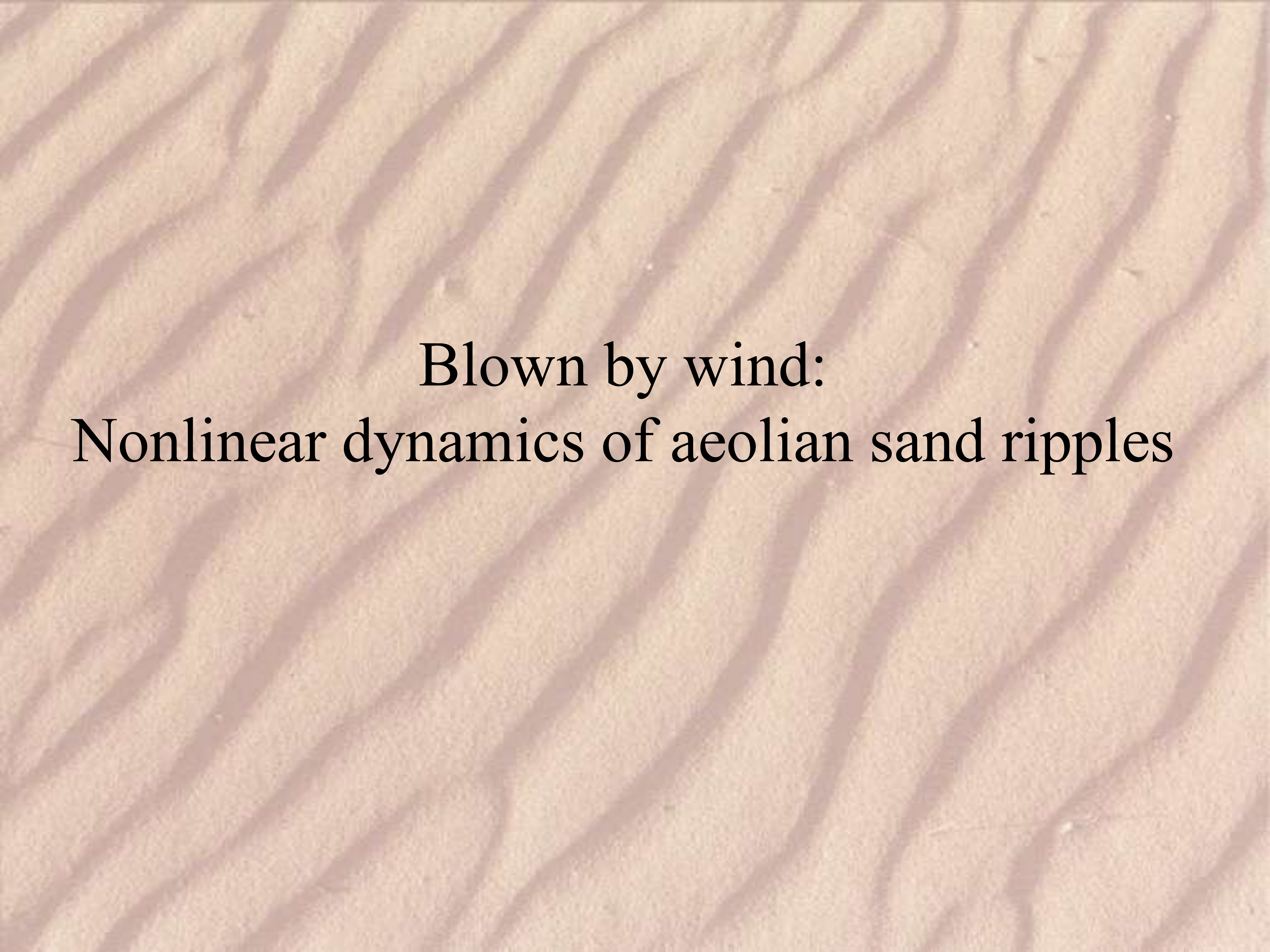
Complex dune structures (Gran Desierto))



http://daac.gsfc.nasa.gov/DAAC_DOCS/geomorphology

Superposed aeolian bedforms

http://daac.gsfc.nasa.gov/DAAC_DOCS/geomorphology



Blown by wind:
Nonlinear dynamics of aeolian sand ripples

Properties of aeolian ripples:

Ripple index about 15-20

Almost 1D bedforms:
crests are perpendicular to the wind, with defects

Slight asymmetry between lee and stoss slopes
(no slip face)

Need of a wind intensity threshold
to have ripple formation

Rapid response to wind

The ripple pattern coarsens with time
and it slowly moves downstream

Grain sorting

A short history of ripple studies:

R.A. Bagnold, *The Physics of Blown Sand and Desert Dunes*, 1941
R. Cooke, A. Warren, A. Goudie, *Desert Geomorphology*, 1993
N. Lancaster, *Geomorphology of desert dunes*, 1995

R.P. Sharp, *J. of Geology*, 1963
M. Seppala and K. Lindé, *Geografiska Annaler*, 1978
B.B. Willetts and M.A. Rice, 1983-1989
J.E. Ungar and P.K. Haff, *Sedimentology*, 1987
R.S. Anderson, *Sedimentology*, 1987
R.S. Anderson, *Earth Sci. Rev.*, 1990

B.T. Werner and D.T. Gillespie, *PRL*, 1993
W. Landry and B.T. Werner, *Physica D*, 1994
H. Nishimori and N. Ouchi, *PRL*, 1993

R.B. Hoyle and A.W. Woods, *PRE*, 1997
L. Prigozhin, *PRE*, 1999
O. Terzidis, P. Claudin and J.-P. Bouchaud, *Eur. Phys. J. B*, 1998
A. Valance and F. Rioual, *Eur. Phys. J. B*, 1999
Z. Csahok and C. Misbah, *Eur. Phys. J. E*, 2000
Z. Csahok, C. Misbah, F. Rioual and A. Valance, *cond-mat*, 2000
H. Yizhaq, N.J. Balmforth, A. Provenzale, Physica D, 2004
H. Yizhaq et al. EPSl, 2019 (megaripples)

Mechanism of ripple formation: aeolian ripples form due to the instability of a flat sand bed exposed to strong wind

When the wind starts to blow,
sand grains are lifted into the air.
These grains are accelerated
by the wind and fall down,
hit the surface,
and eject other grains.

The rebounding (saltating) grains
are then accelerated by the wind,
and a cascade process ensues.

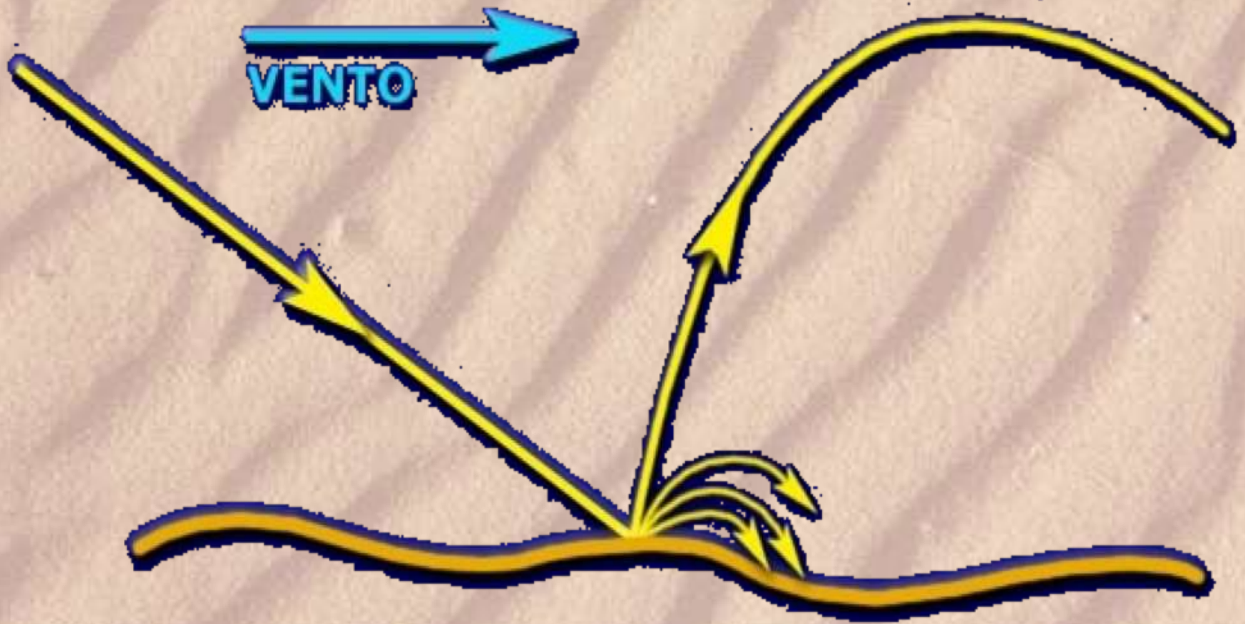
An entire population
of saltating grains emerges.
The height of the saltation layer
can be about one meter in strong winds

Hypotheses of ripple formation (Cooke et al, 1993):

1. A rithmic barrage of saltating grains (Bagnold)

2. The wave hypothesis:
    a) The bed as a fluid
    b) The saltation curtain as a fluid
    c) Wave-like instabilities in the boundary layer
    d) Secondary motions in the lee of transverse ripples

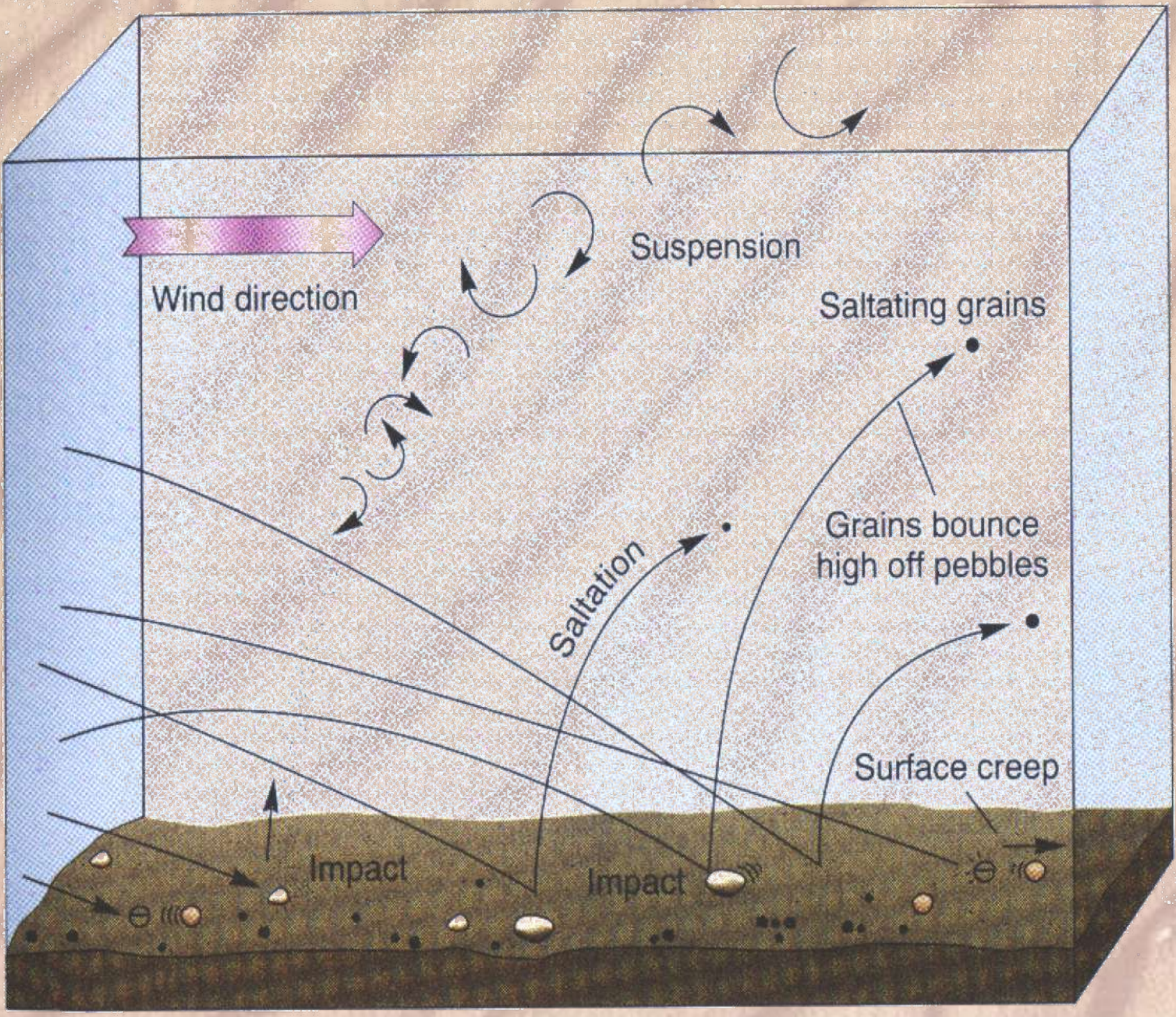
3. The role of reptating grains (Anderson 1987)



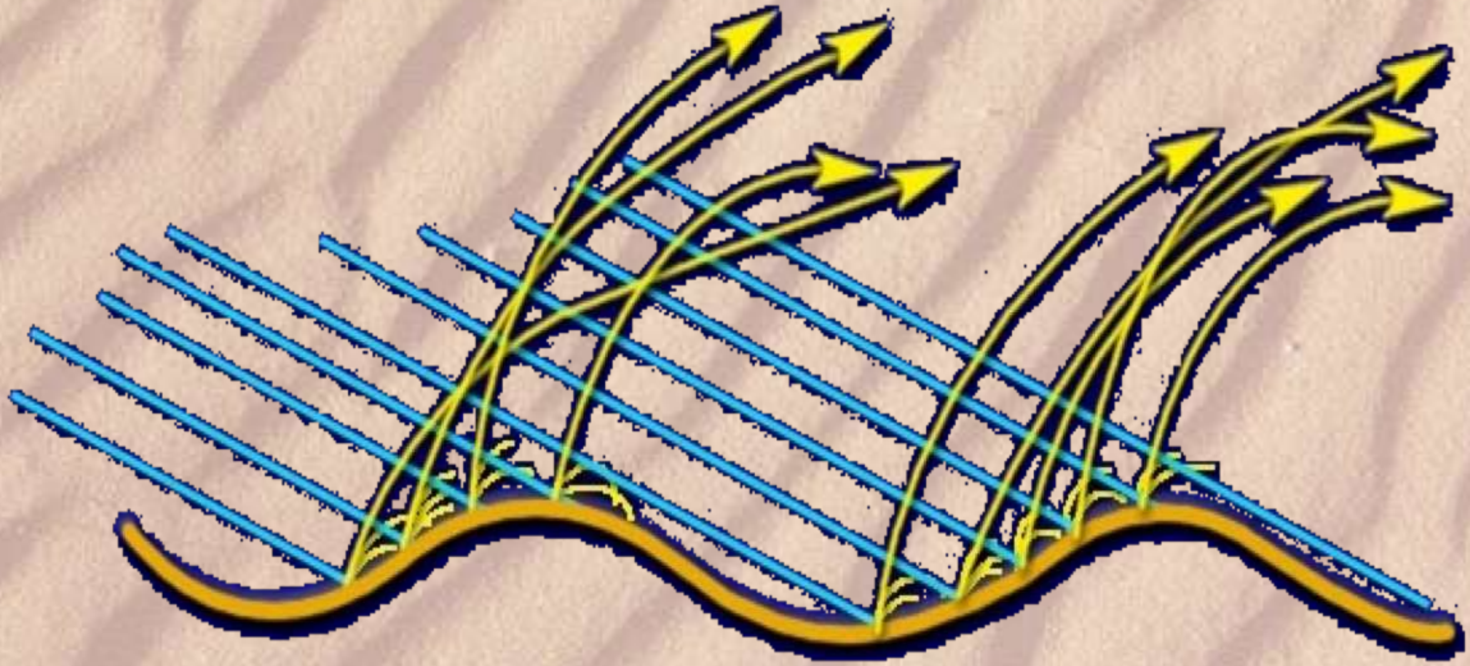
Saltation with typical jump length *L*

Reptation with typical jump length $a \ll L$

L is about *1 m* and *a* is about *1 cm*

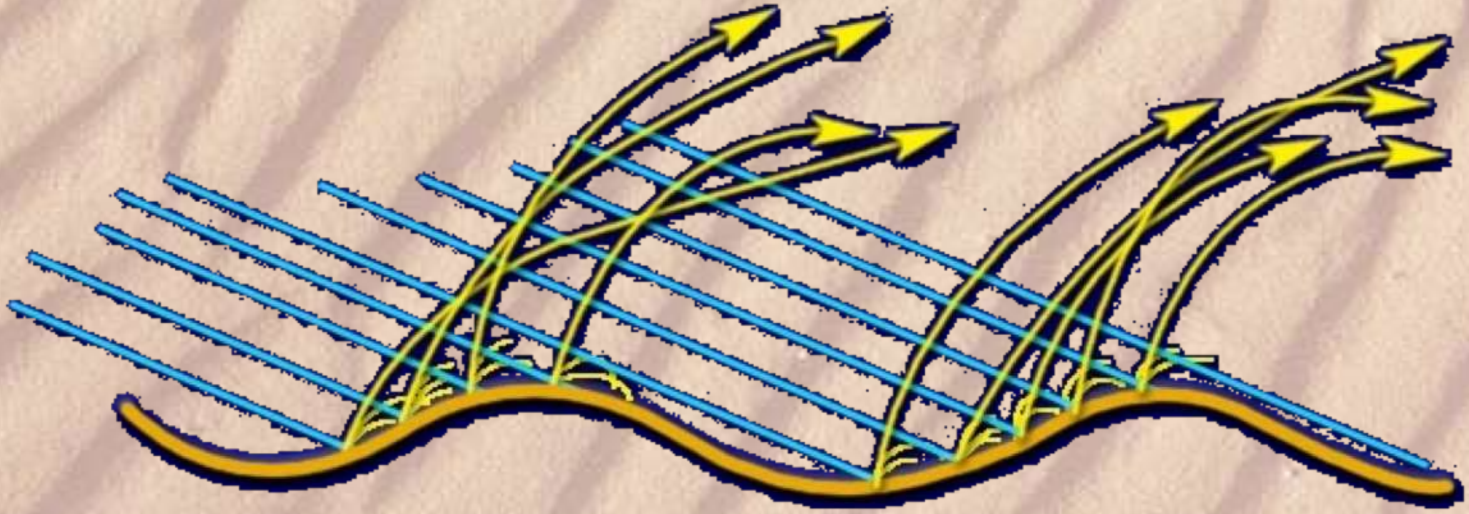

Suspension
Wind direction
Saltating grains
Grains bounce high off pebbles
Saltation
Surface creep
Impact
Impact

Upon impact,
the energy of a saltating grain goes as:
80% to one (on average) rebounding grain,
10% to a few reptating grains,
10% to the deformation of the bed



Depth of the saltation layer: up to about 1 m

Depth of the reptation layer: a few mm



We can idealize the problem
in terms of a sand surface bombarded
by a continuous flux of saltating grains
that hit the surface at constant (small) angle $\phi = 8\text{-}12^\circ$

The saltating grains drive the system.
The important dynamics is contained in
the behavior of the reptating grains

Conservation of sand

$$(1-n)\rho\frac{\partial\zeta}{\partial t} = -\nabla\cdot\mathbf{Q}$$

- n porosity of the bed (about 0.35)
- ρ density of sand
- ζ elevation of the sand surface
- $\mathbf{Q}$ flux of sand grains

The flux of sand:

$$\mathbf{Q} = \mathbf{Q}_s + \mathbf{Q}_r$$

- $\mathbf{Q}_s$ flux of saltating grains
- $\mathbf{Q}_r$ flux of reptating grains

The flux of saltating grains is assumed to be constant for aeolian ripples

$$\nabla \cdot \mathbf{Q}_s = 0$$

All the dynamics is contained in the variability of the reptation flux

NB: This is untenable for megaripples and dunes

There is no feedback of the
aeolian bedforms
on the wind
and on the flux of saltating grains

NB: This is untenable for dunes

1D case

if all the grains had the same reptation length *a*

$$Q_r^{bare}(x,t) = m \int_{x-a}^{x} N_{ej}(x')\,dx'$$

- m mass of a sand grain
- N_{ej} number of ejected grains
- N_r average number of reptating grains ejected by one saltating grain
- $N_{ej} = N_r N_{im}$ where N_{im} is the number of impacting grains

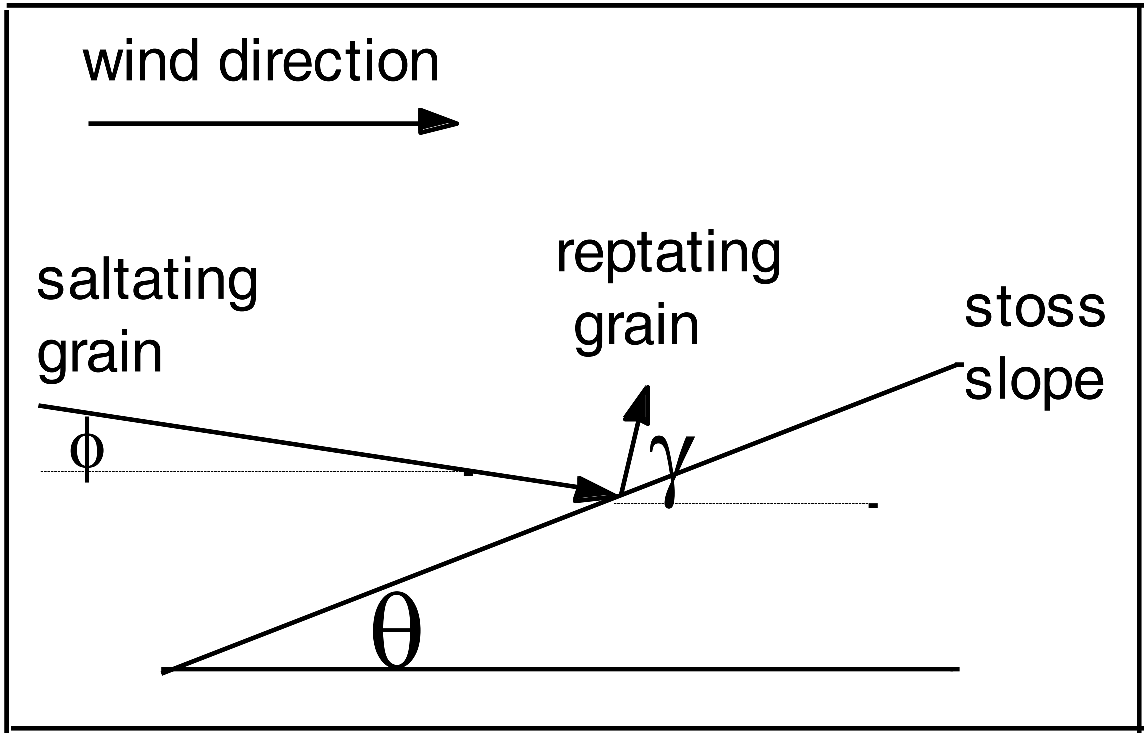
For a distribution of reptation lengths

$$Q_r^{bare}(x,t) = m \int_{-\infty}^{\infty} d\alpha \; p(\alpha) \int_{x-\alpha}^{x} N_{ej}(x')\,dx'$$

- m mass of a sand grain
- N_{ej} number of ejected grains
- N_r average number of reptating grains ejected by one saltating grain
- $N_{ej} = N_r N_{im}$ where N_{im} is the number of impacting grains
- $p(\alpha)$ distribution of reptation lengths

$$\int \alpha p(\alpha)\,d\alpha = a$$

Important angles



Number density of impacting grains

$$N_{im}(x) = N_{im}^{0}\left(1 + \frac{\tan\theta}{\tan\phi}\right)\cos\theta$$

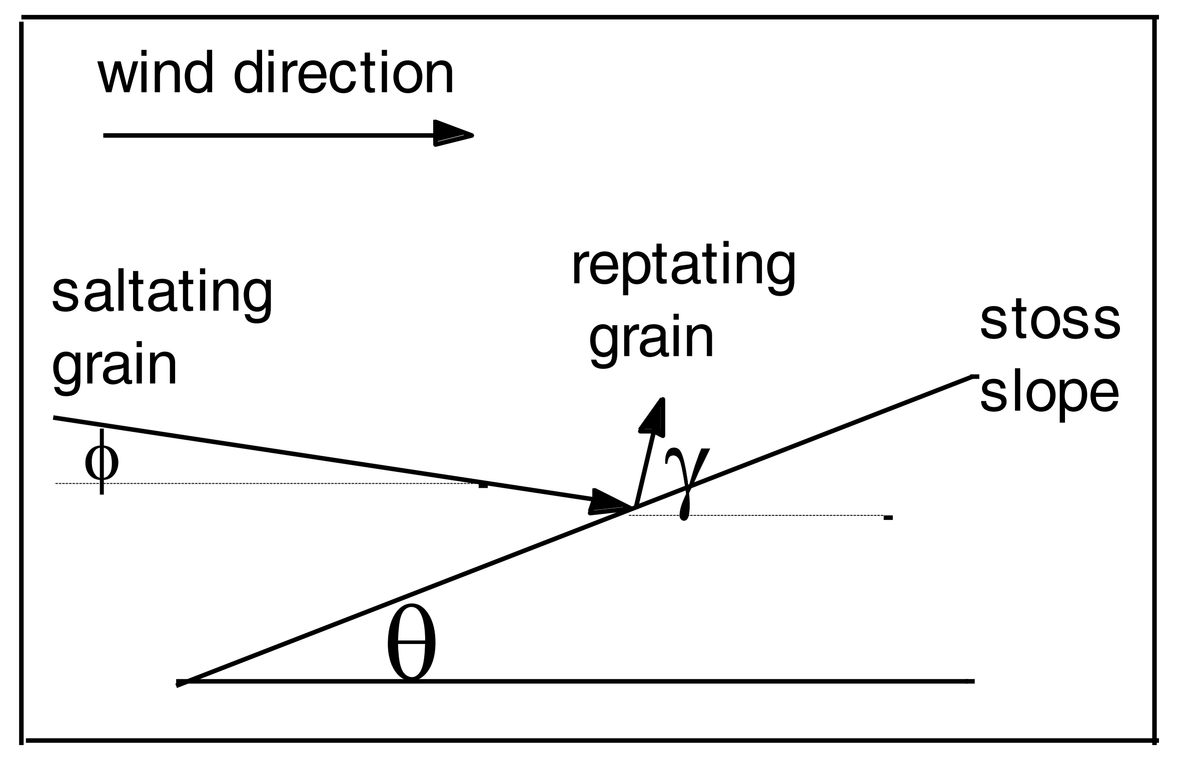
$$= N_{im}^{0}\cot\phi\ \frac{\tan\phi + \zeta_x}{\sqrt{1+\zeta_x^2}}$$

$N_{im}{}^{0}$ number density of impacting grains on a horizontal surface (about 10^7 m^{-2} s^{-1})

θ inclination of the surface

$\tan\theta = \zeta_x$

$$a = 2\frac{V^2}{g}\frac{\sin(\gamma - \theta)\cos\gamma}{\cos\theta} = a_{hor}(1 - \cot\gamma\tan\theta)$$



Shadowing: the flux of reptating grains becomes

$$N_{im}(x) = N_{im}^{0} \cot\phi \, Max \left\{ \frac{\tan\phi + \zeta_x}{\sqrt{1+\zeta_x^2}}, \, 0 \right\}$$

The full integral model:

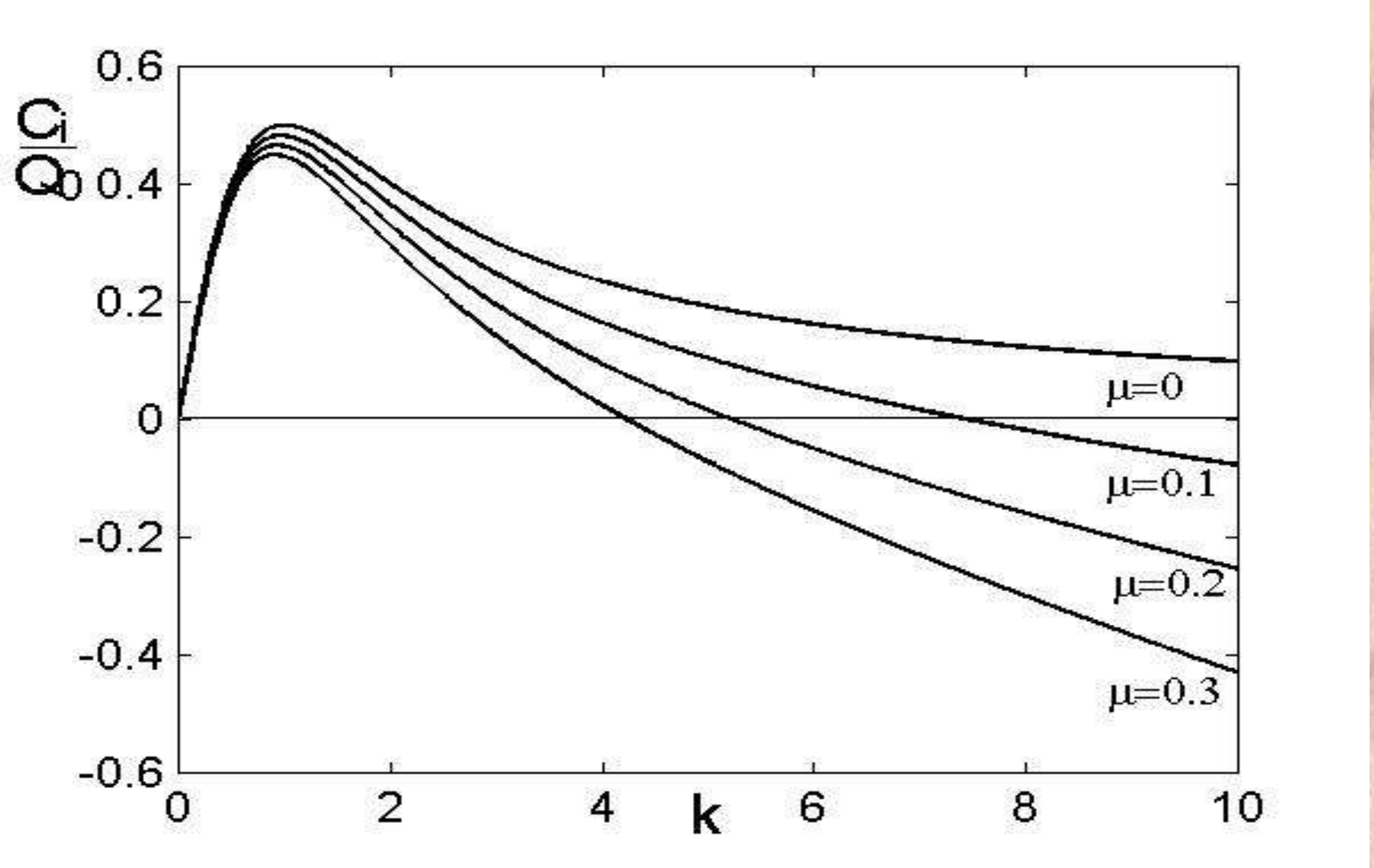
$$\frac{\partial \zeta}{\partial t} = -Q_0 \frac{\partial}{\partial x}\left[\left(1-\mu\zeta_x\right)\int_{-\infty}^{\infty} d\alpha\, p(\alpha) \int_{x-\alpha}^{x} F(x')\, dx'\right]$$

$$F(x) = Max\left\{\frac{\tan\phi + \zeta_x}{\sqrt{1+\zeta_x^2}}, 0\right\}$$

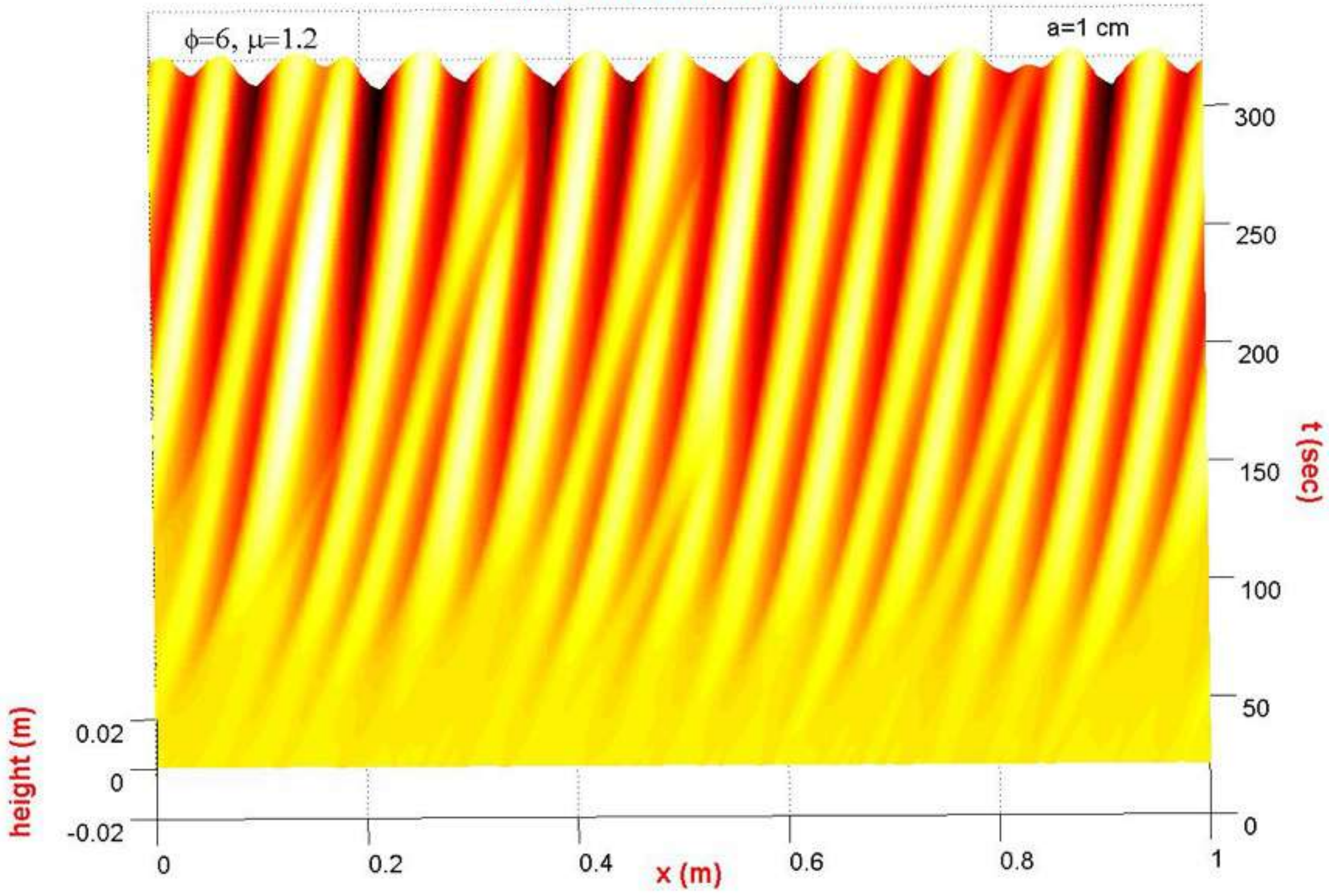
$$Q_0 = \frac{mN_r N_{im}^0 \cot\phi}{\rho\left(1-n\right)}$$

Linear stability analysis

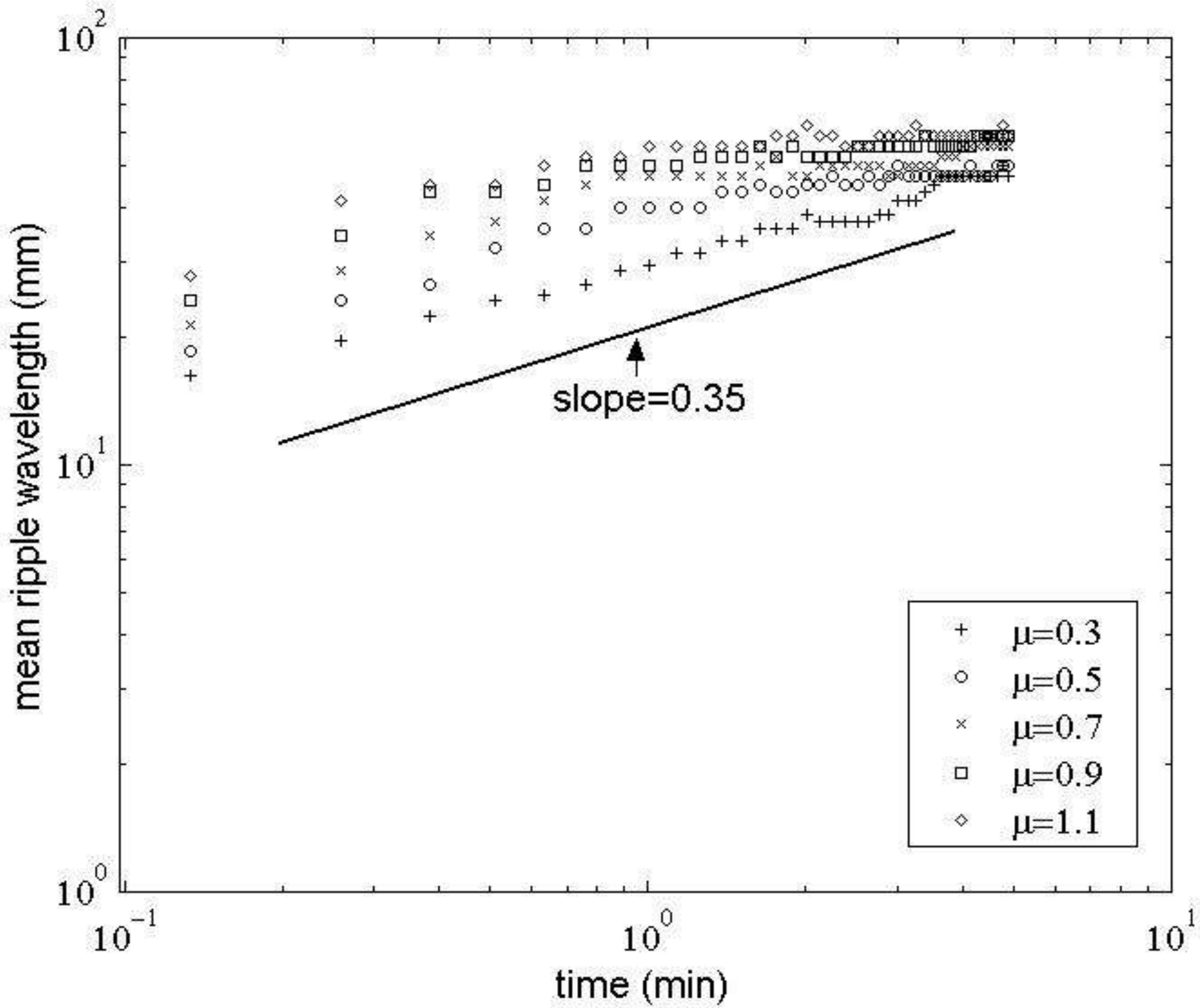
$$Q_r(x,t) = Q_r^{bare}(x,t)\ (\ 1 - \mu\ \zeta_x\ )$$

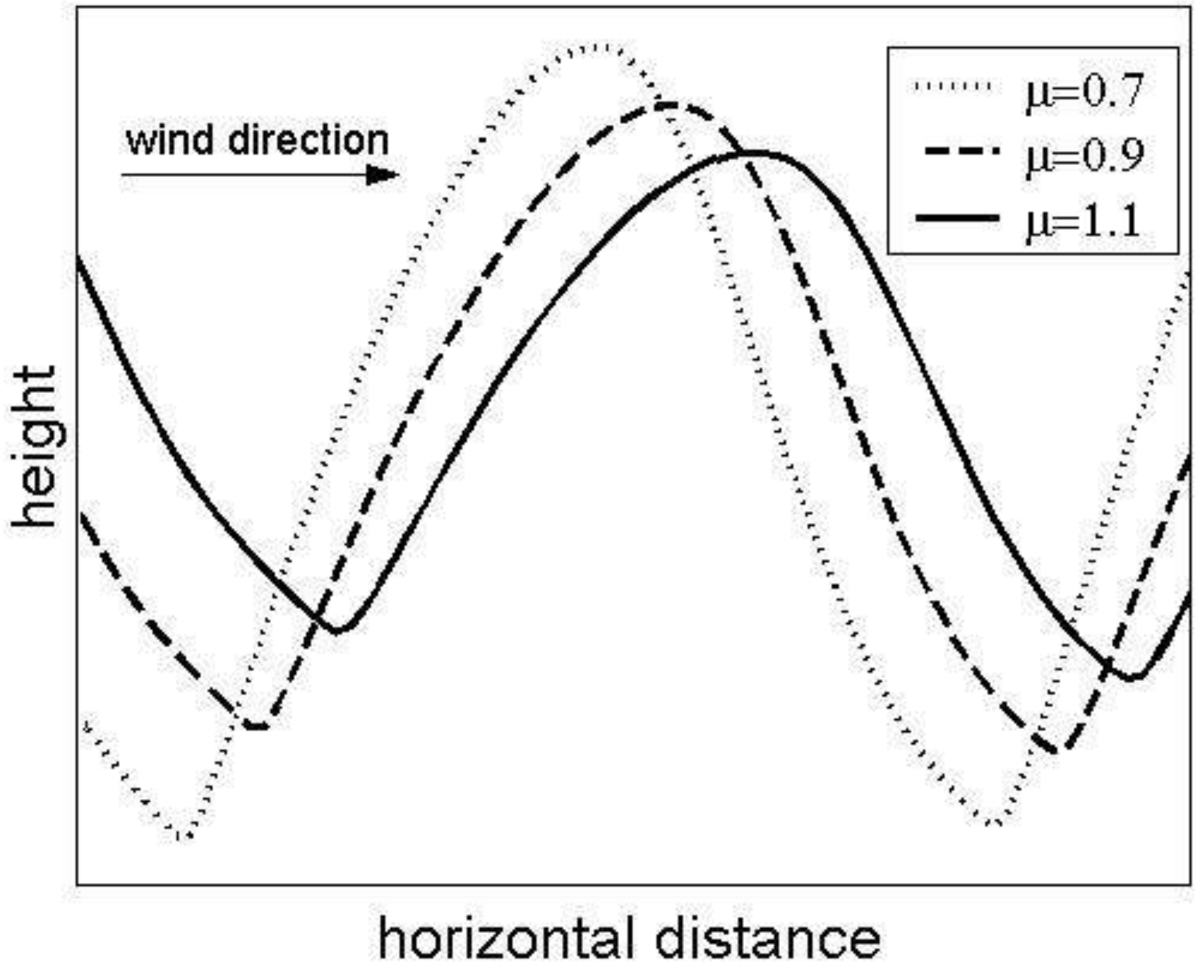


Time Evolution of Ripples



Coarsening of the ripple pattern





wind direction
μ=0.7
μ=0.9
μ=1.1
height
horizontal distance

An extension to the 2D case:

If all the grains had
the same jump length a,
the flux at (x,y)
in the direction ψ to the x axis
is assumed to be proportional to
the number of grains ejected
between $(x - a \cos \psi , y - a \sin \psi)$ and (x,y)

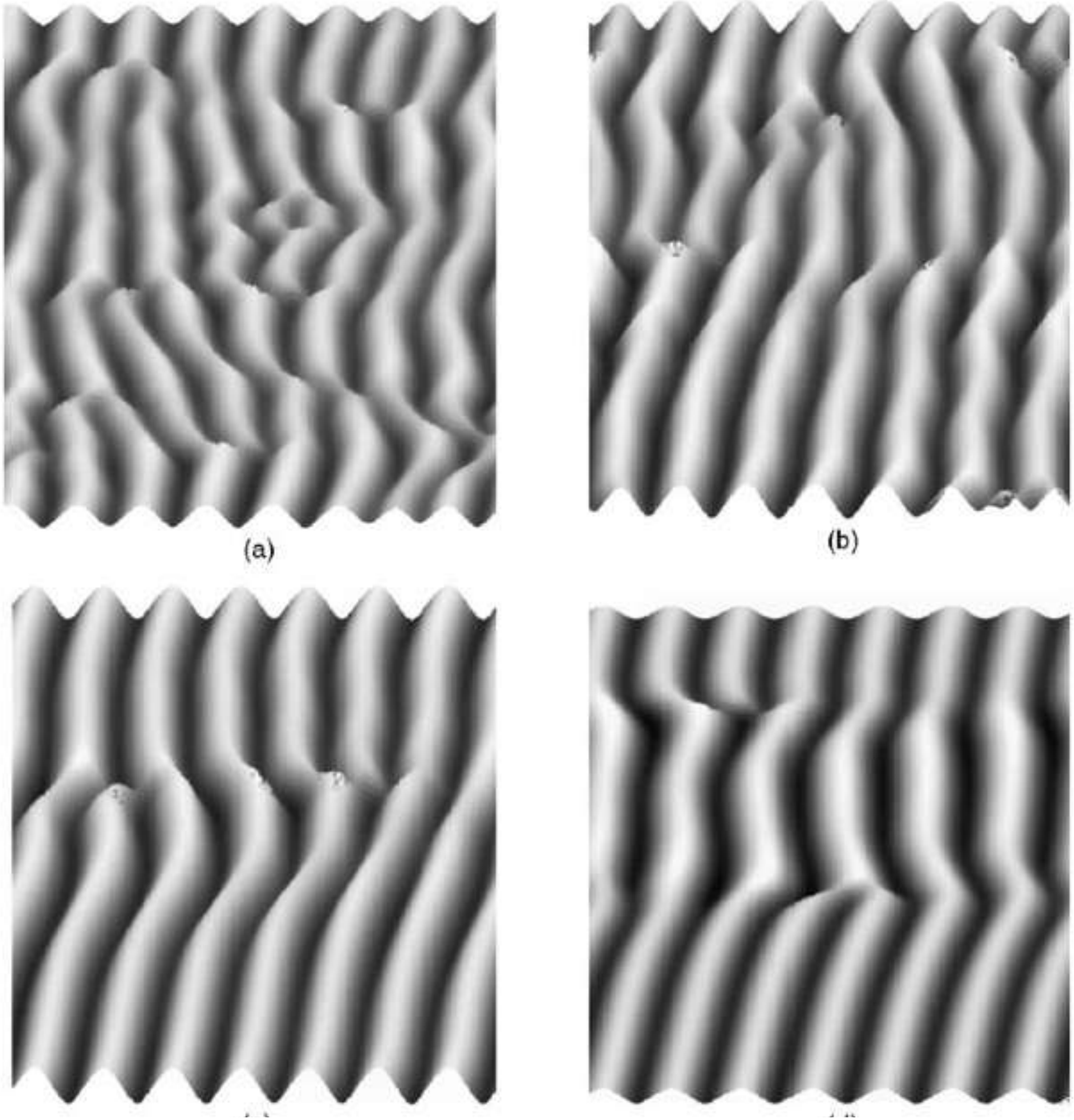
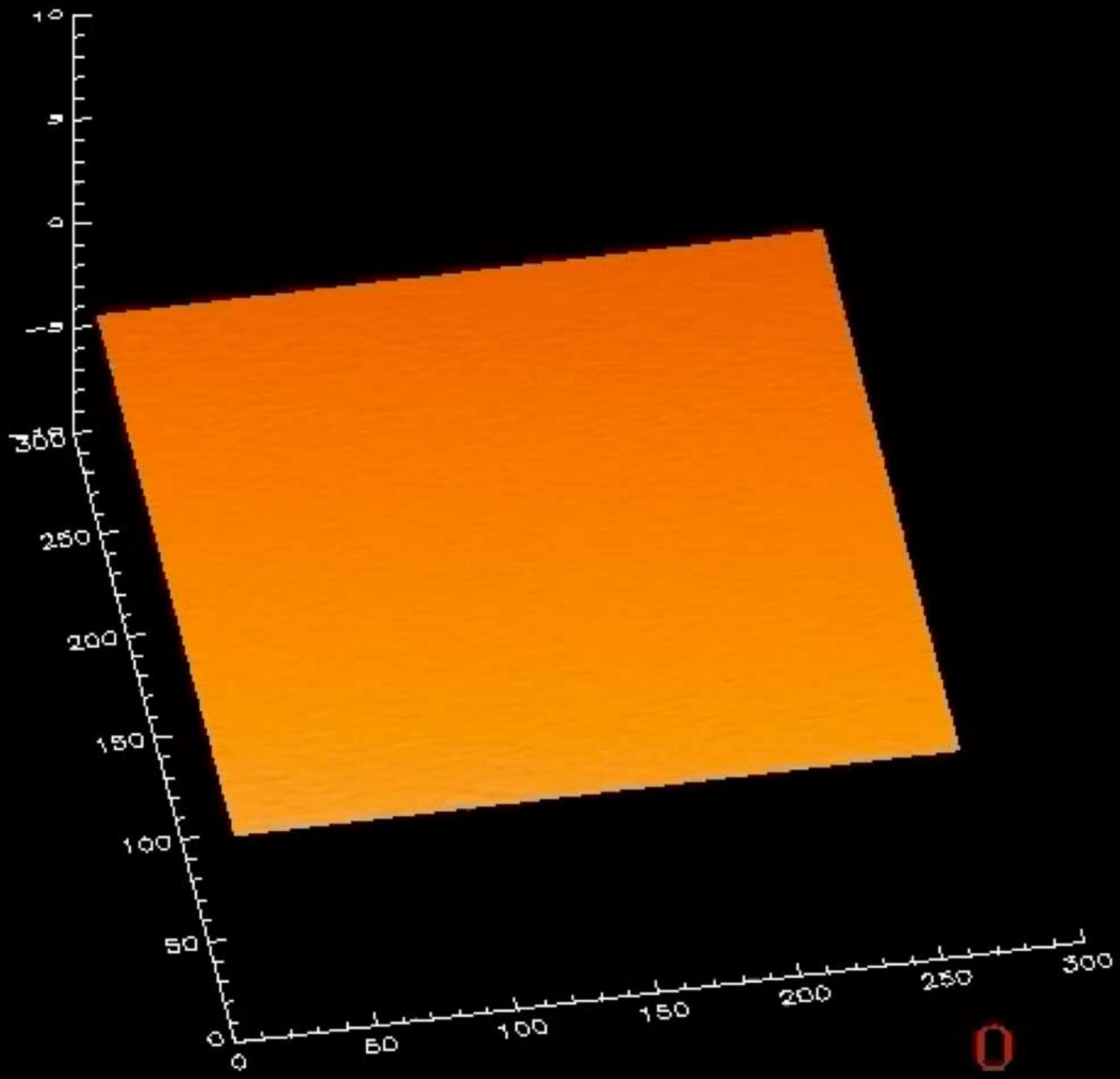
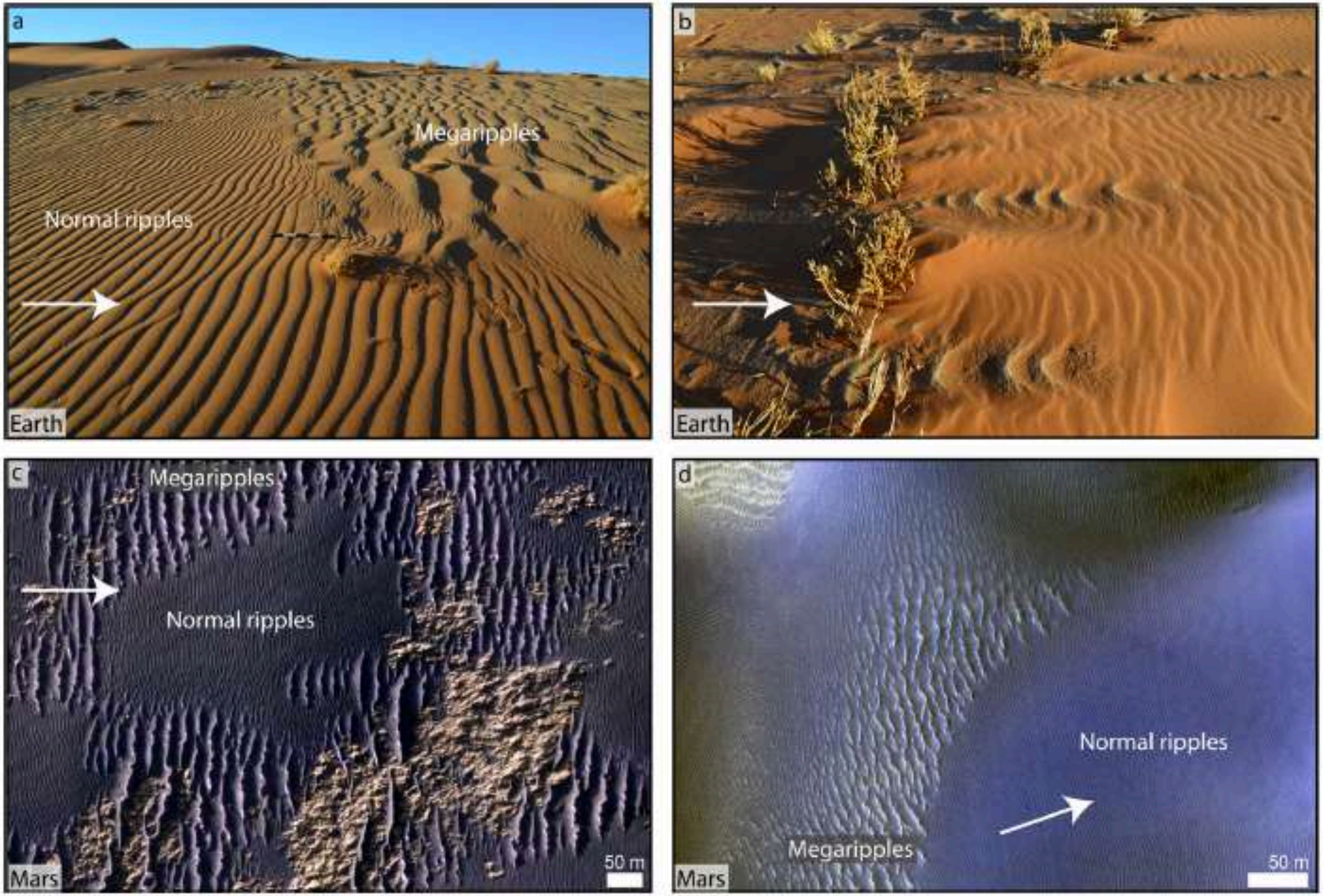


Fig. 12. Snapshots of a two-dimensional ripple field produced by the numerical integration of Eq. (28) on a 256×256 grid with periodic boundary condition, at $T = 2, 4, 8, 16$. The wind direction is from left to right. Parameter values: $\epsilon = \mu = 0.25$, $\phi = 10^\circ$, $\beta_1 = \beta_3 = 1$, $\beta_2 = \tan\phi$ and a domain size of $5\pi/2$.


10
5
0
-5
300
250
200
150
100
50
0
0
50
100
150
200
250
300
0

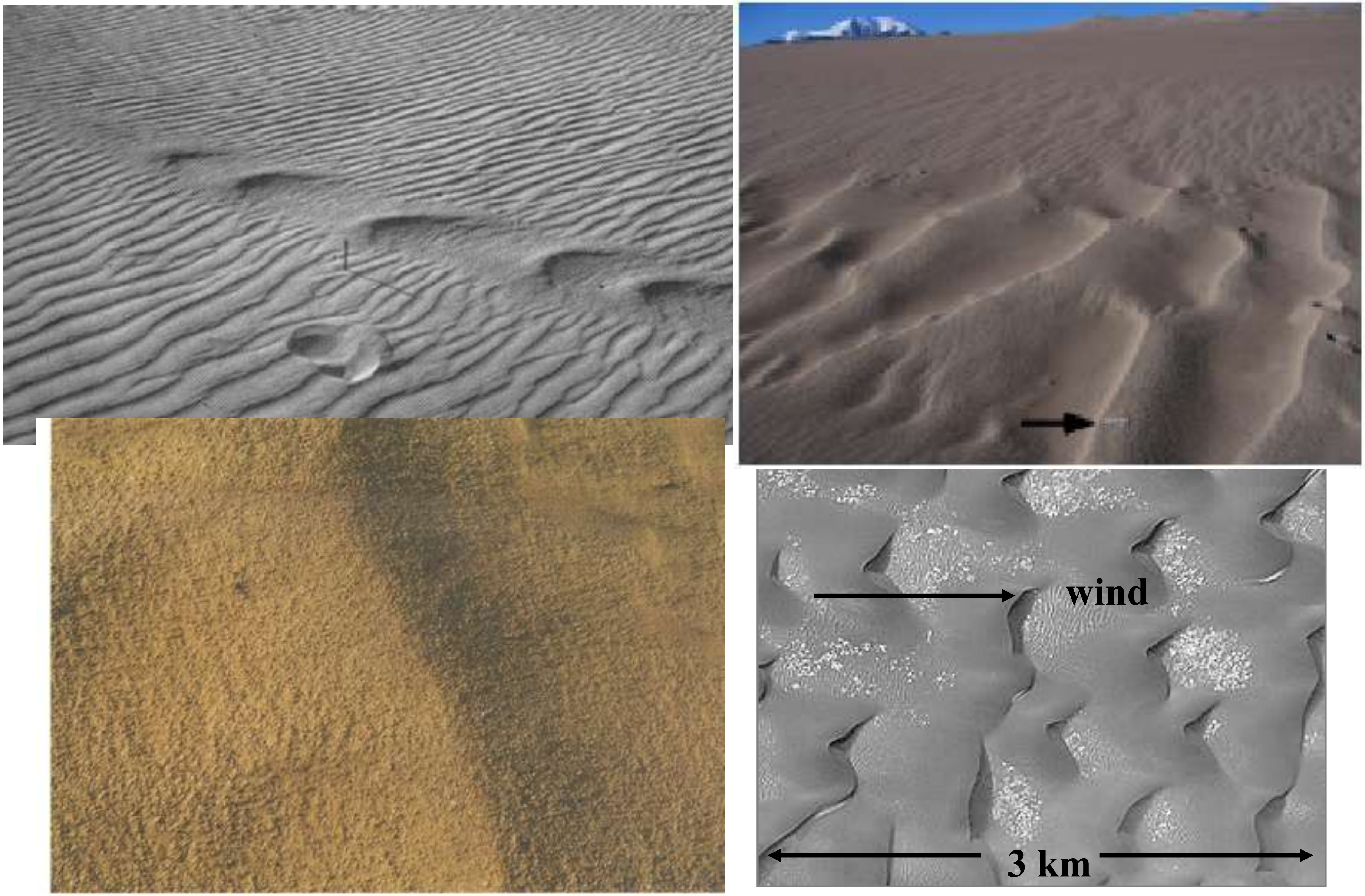


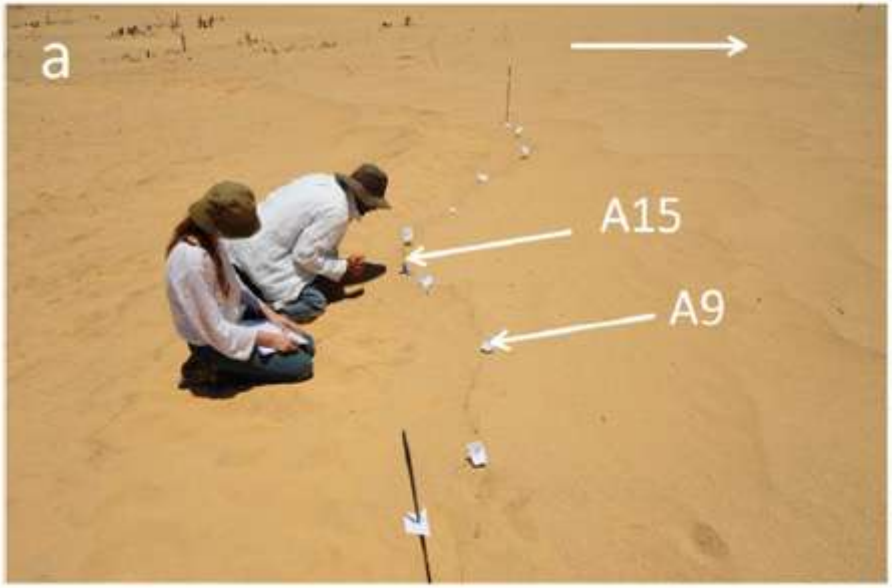
Megaripples on Earth and Mars

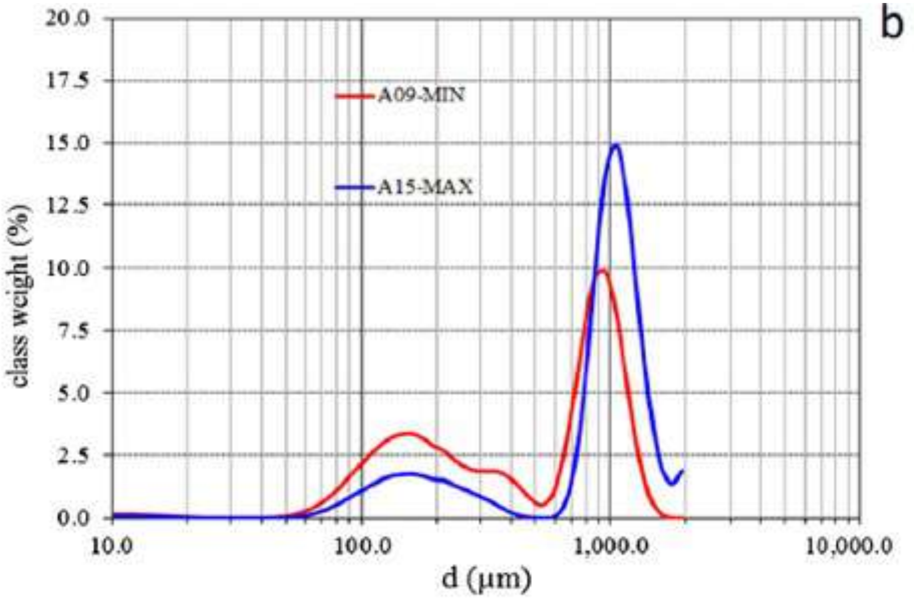
The origin of the transverse instability of aeolian megaripples

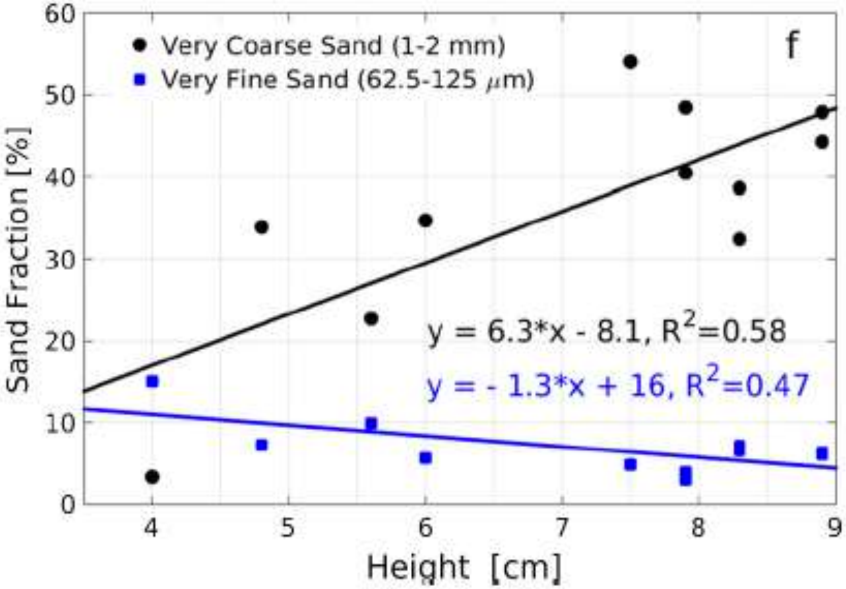
H. Yizhaq[a,*], G. Bel[a,b], S. Silvestro[c,d], T. Elperin[e], J.F. Kok[f], M. Cardinale[g], A. Provenzale[h], I. Katra[i]

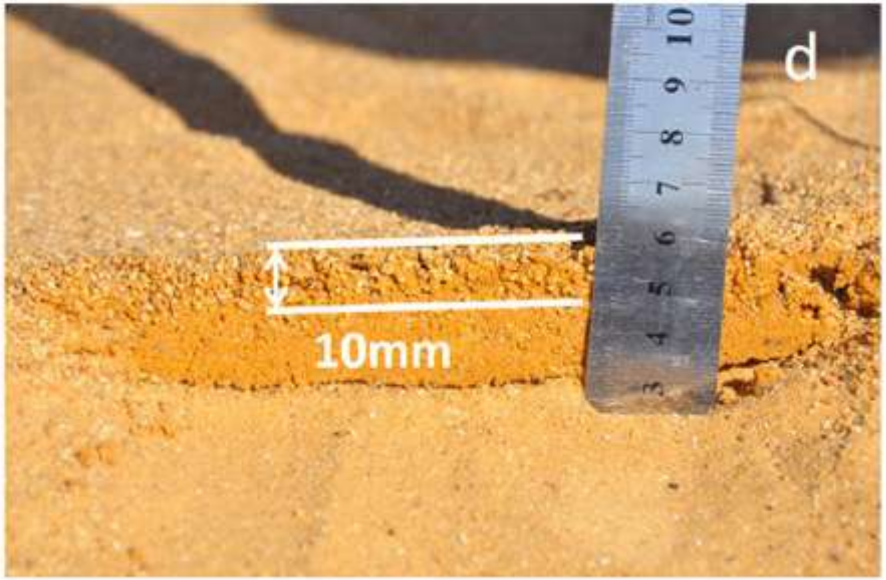
Earth and Planetary Science Letters 512 (2019) 59–70



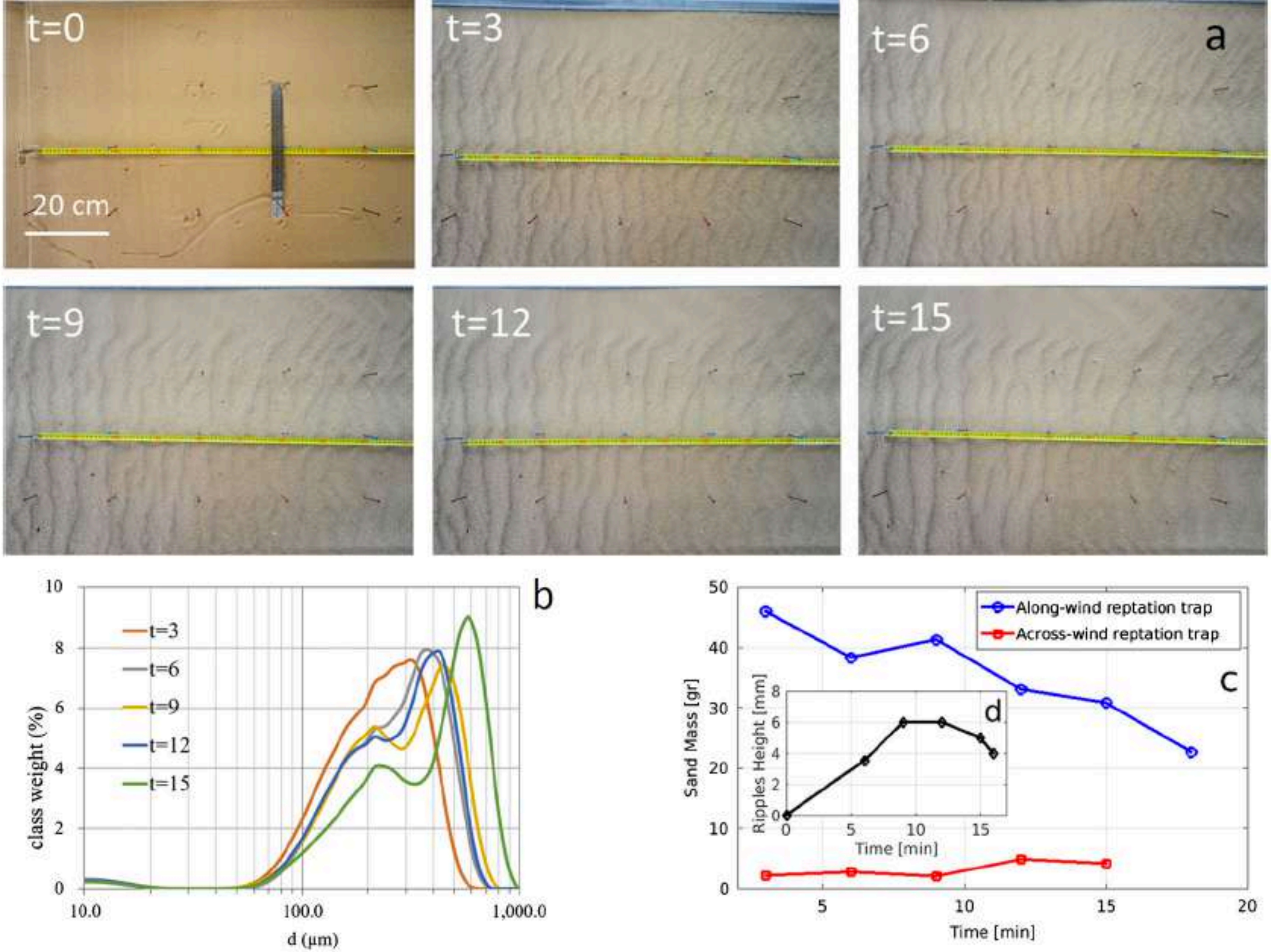

a
A15
A9


b
A09-MIN
A15-MAX
class weight (%)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
10.0
100.0
1,000.0
10,000.0
d (µm)

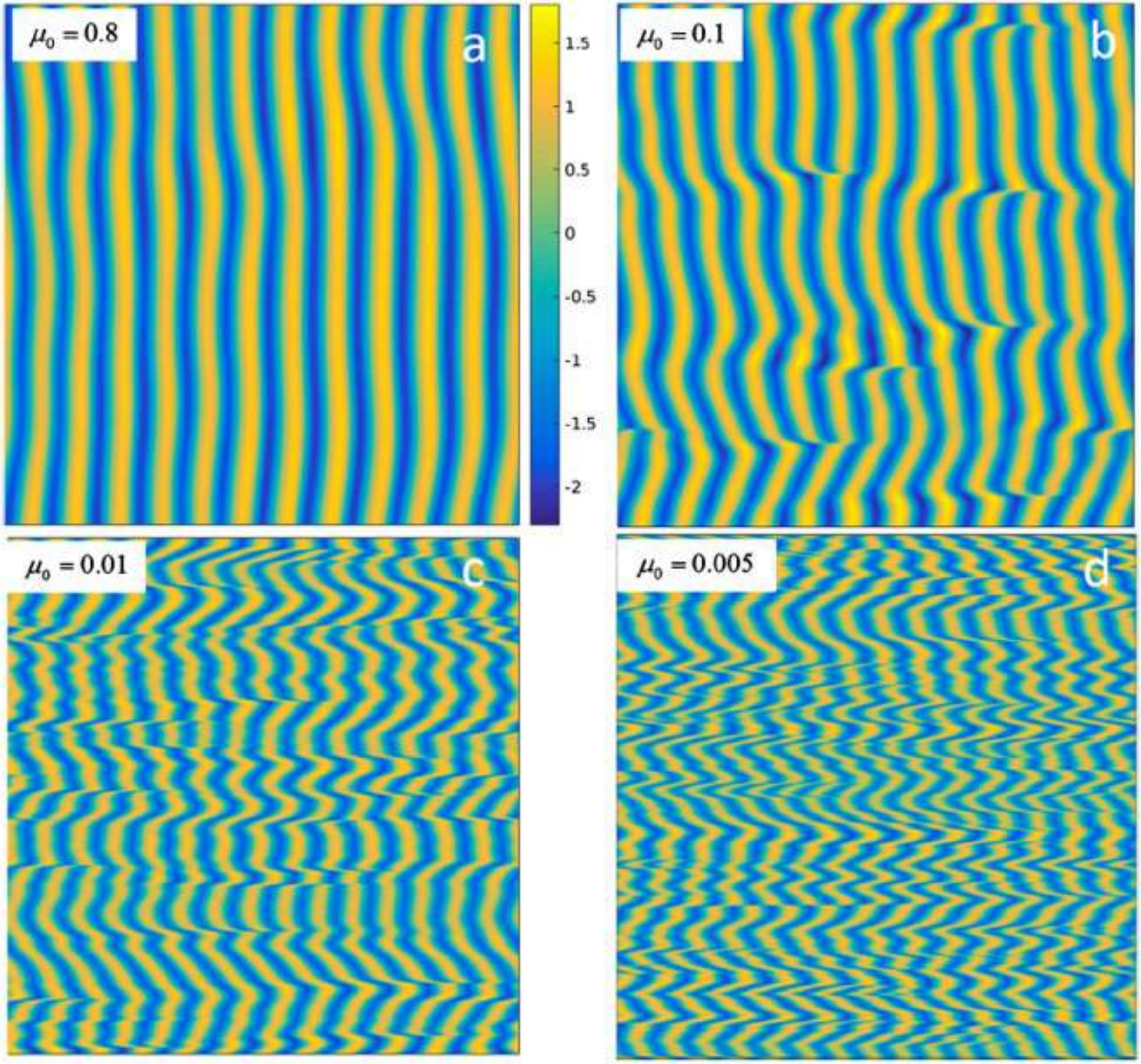

f
Very Coarse Sand (1-2 mm)
Very Fine Sand (62.5-125 µm)
y = 6.3*x - 8.1, R²=0.58
y = - 1.3*x + 16, R²=0.47
Sand Fraction [%]
0
10
20
30
40
50
60
4
5
6
7
8
9
Height [cm]


d
10mm

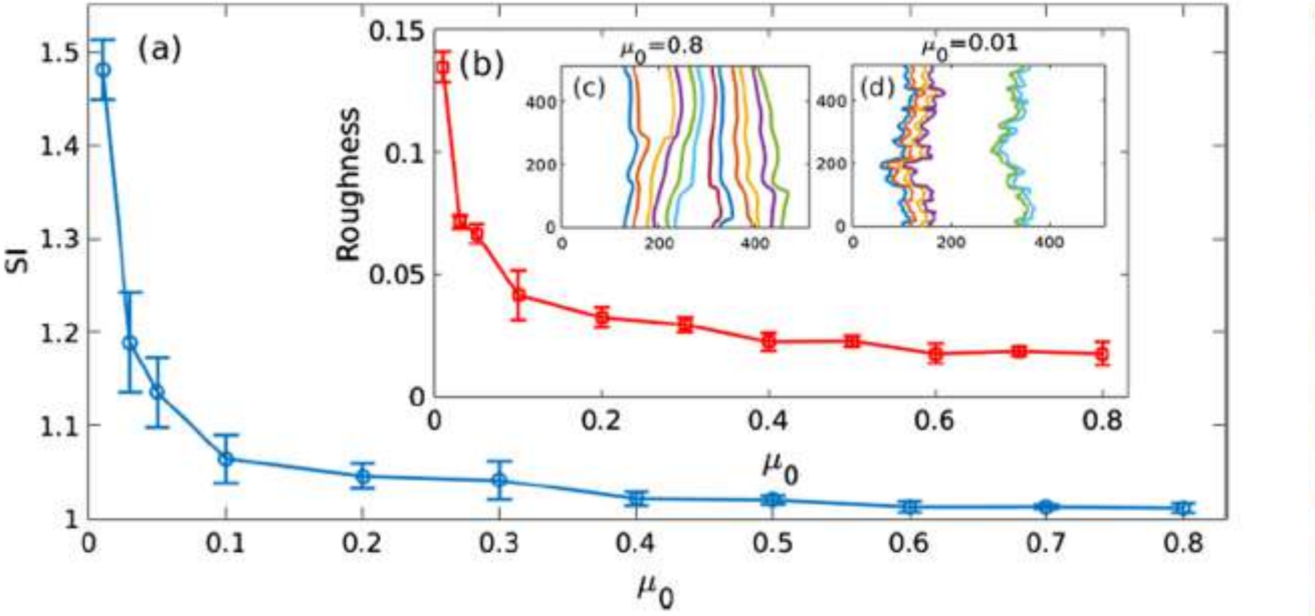
Field work

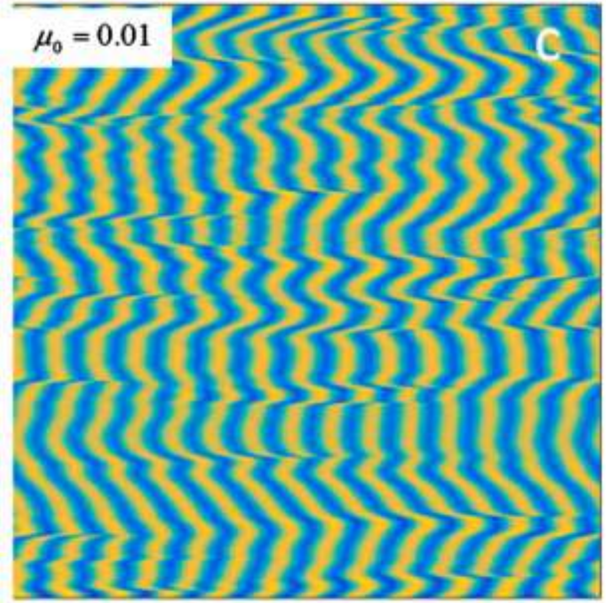


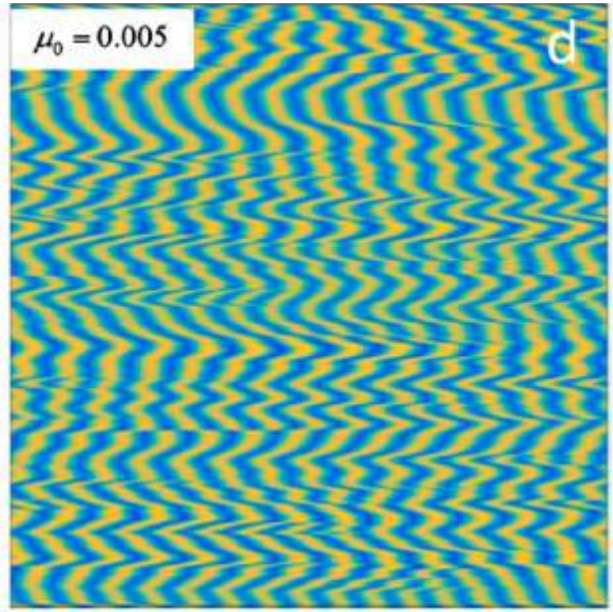
Laboratory experiments



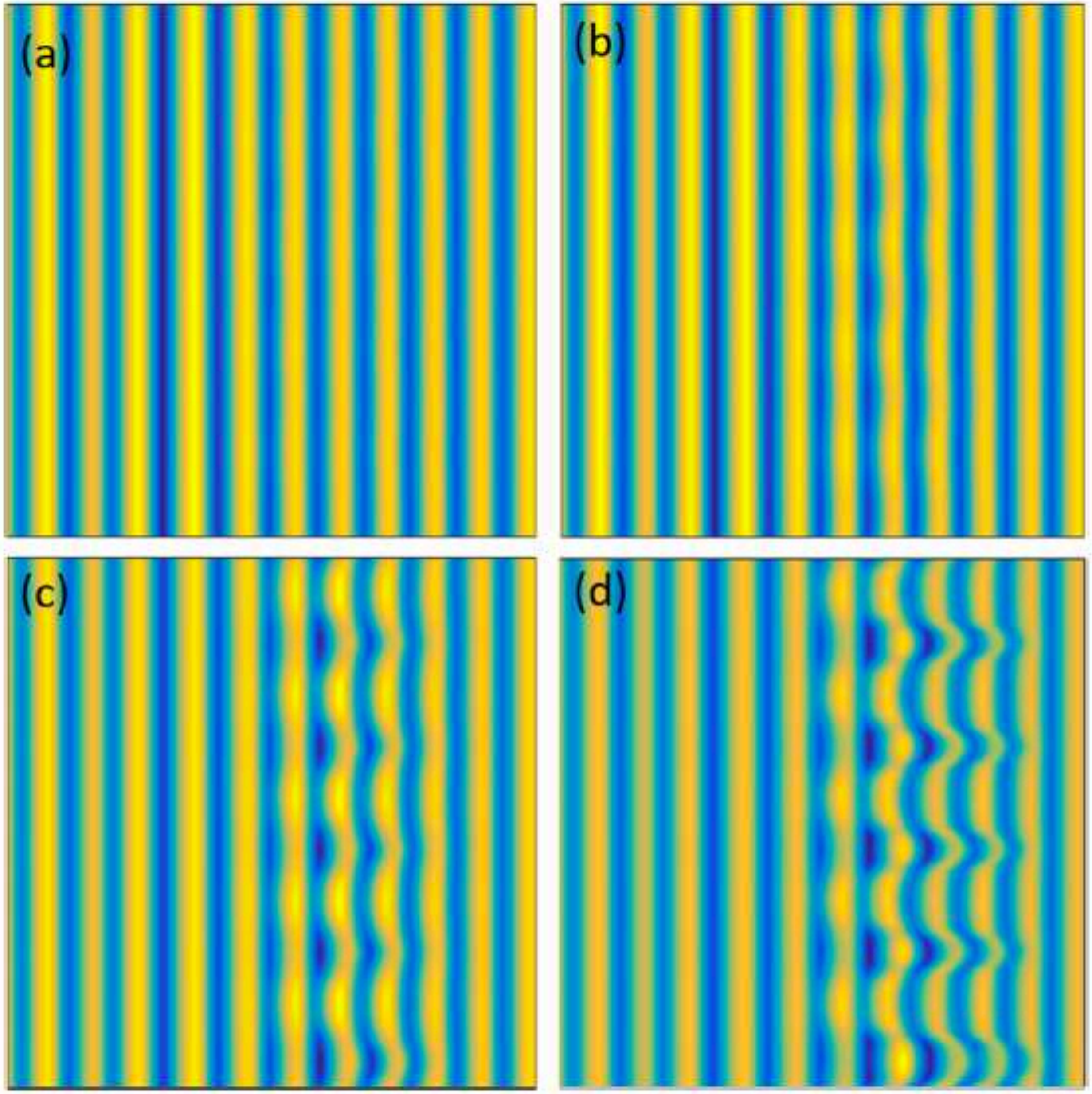
Numerical simulations



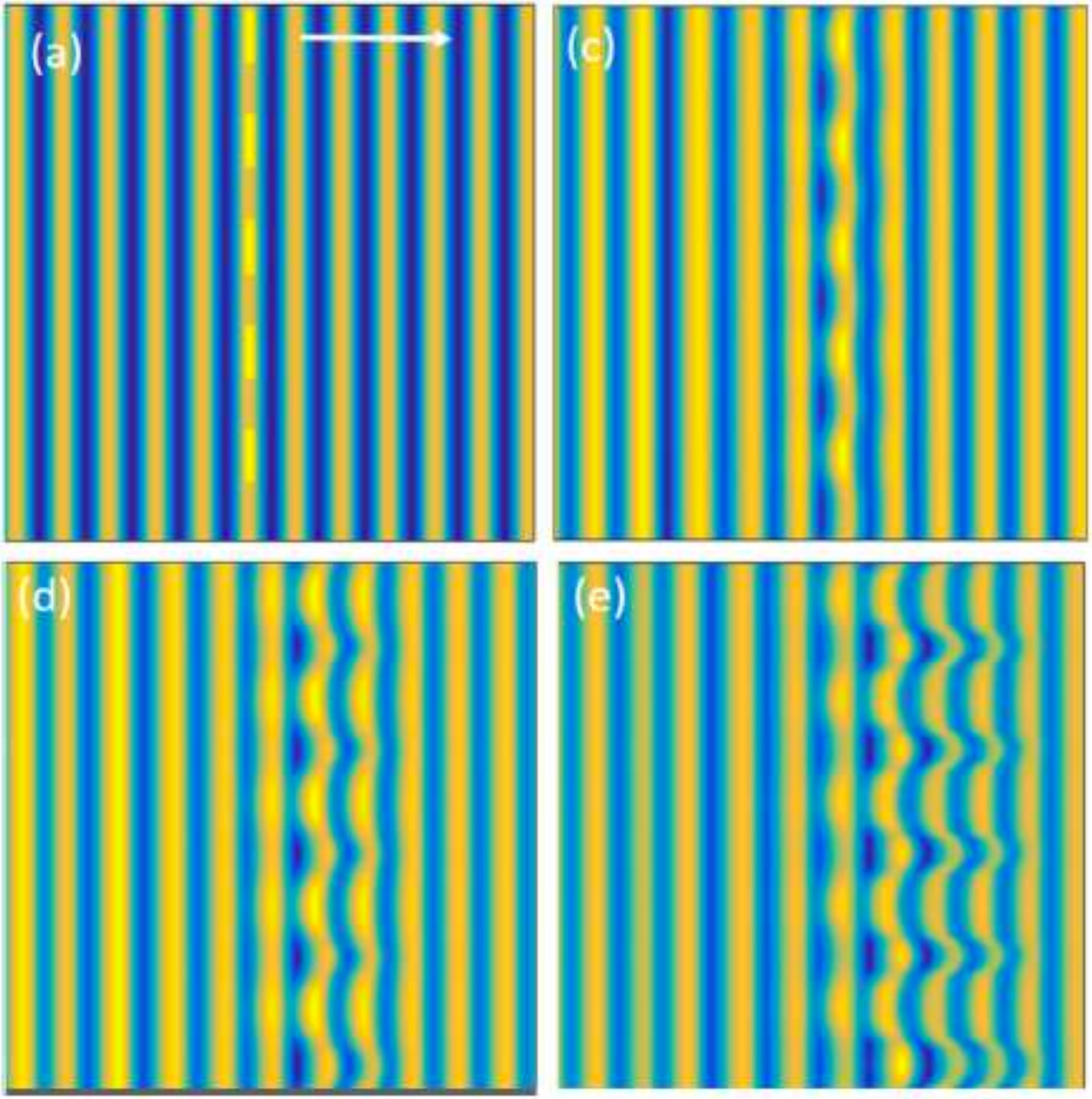




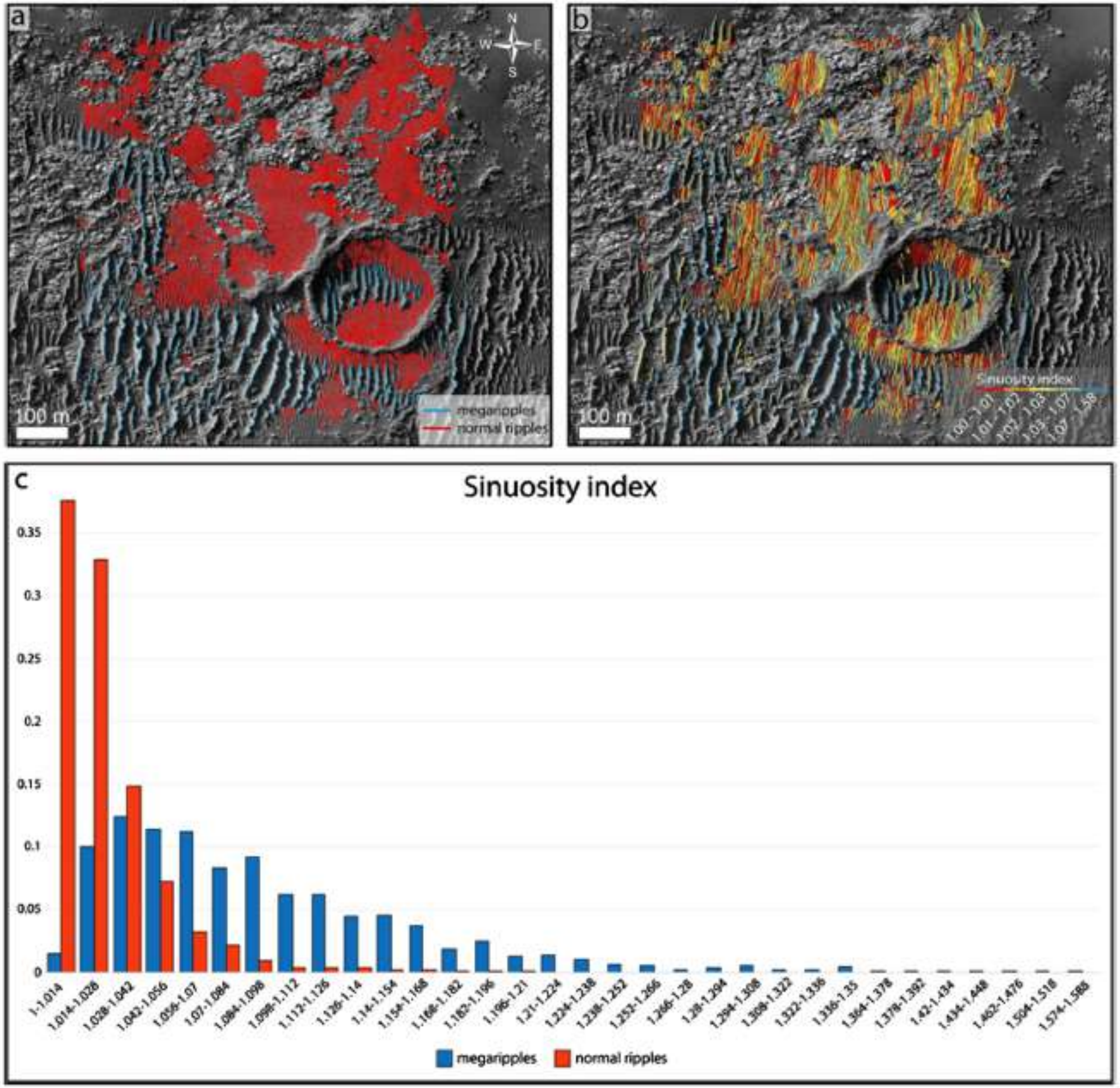
Numerical simulations



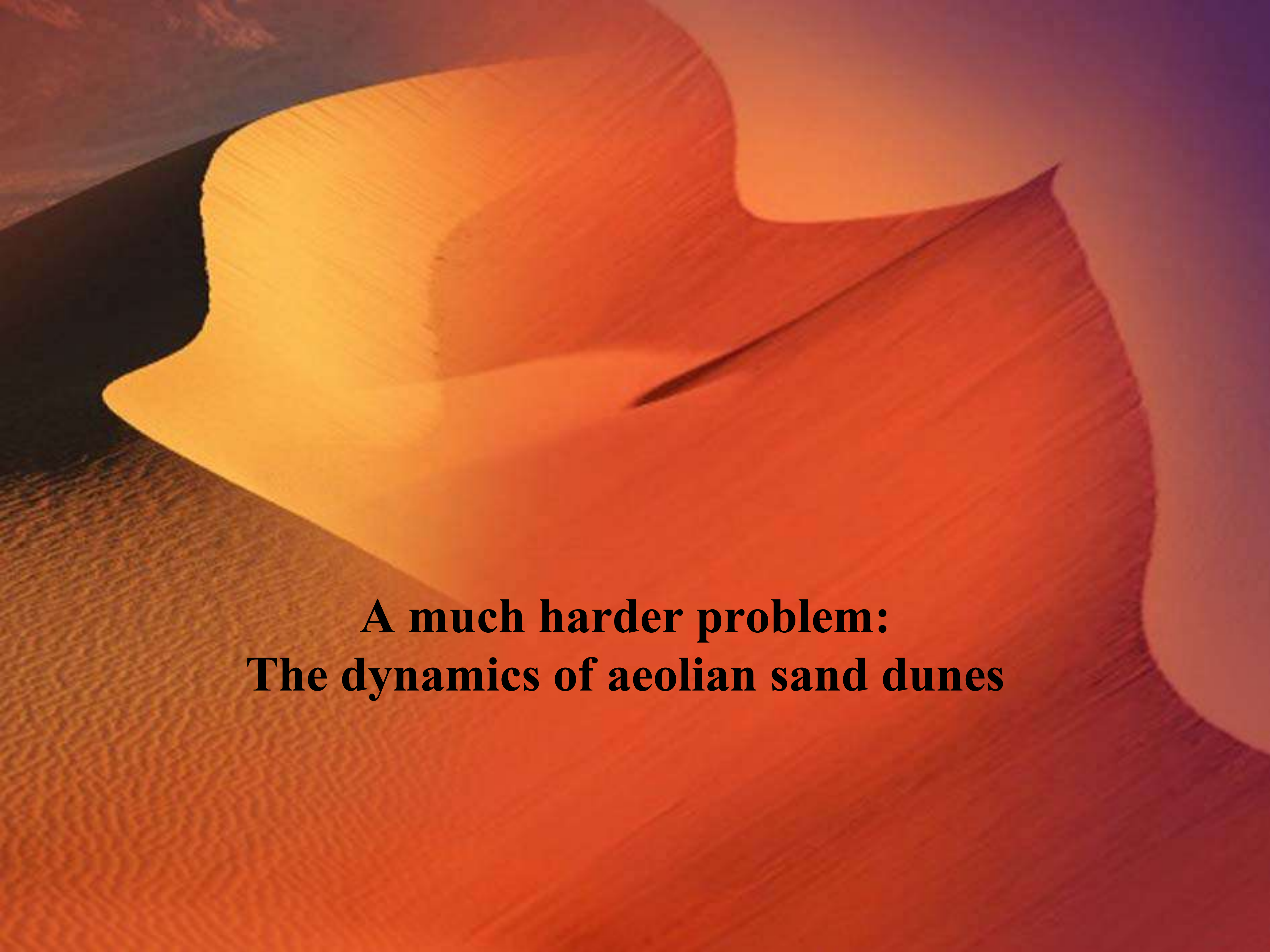
Numerical simulations



Lateral flux dependent on height

a
N
W
E
S
100 m
megaripples
normal ripples
b
100 m
Sinuosity index
1.00 - 1.01
1.01 - 1.02
1.02 - 1.03
1.03 - 1.07
1.07 - 1.58
c
Sinuosity index
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1-1.014
1.014-1.028
1.028-1.042
1.042-1.056
1.056-1.07
1.07-1.084
1.084-1.098
1.098-1.112
1.112-1.126
1.126-1.14
1.14-1.154
1.154-1.168
1.168-1.182
1.182-1.196
1.196-1.21
1.21-1.224
1.224-1.238
1.238-1.252
1.252-1.266
1.266-1.28
1.28-1.294
1.294-1.308
1.308-1.322
1.322-1.336
1.336-1.35
1.364-1.378
1.378-1.392
1.42-1.434
1.434-1.448
1.462-1.476
1.504-1.518
1.574-1.588
megaripples
normal ripples

Mars case



A much harder problem:
The dynamics of aeolian sand dunes

Emma Pike - Originally uploaded to English Wikipedia

By Hannes Grobe 21:14, 26 October 2007 (UTC) - Own work, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=2978390

Just a beginning in the fascinating world of (eco)geomorphological pattern modelling