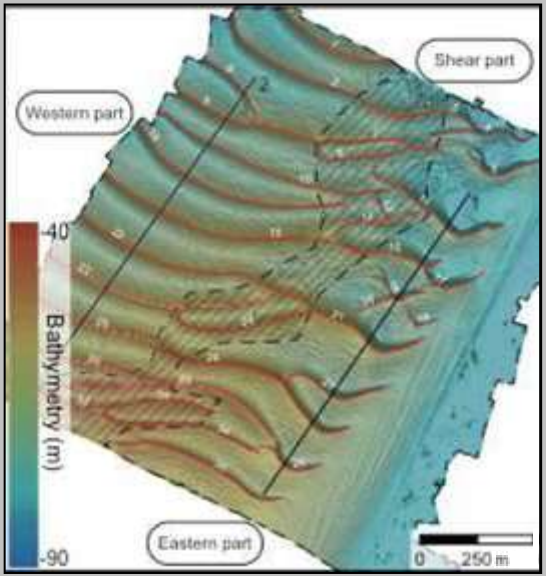
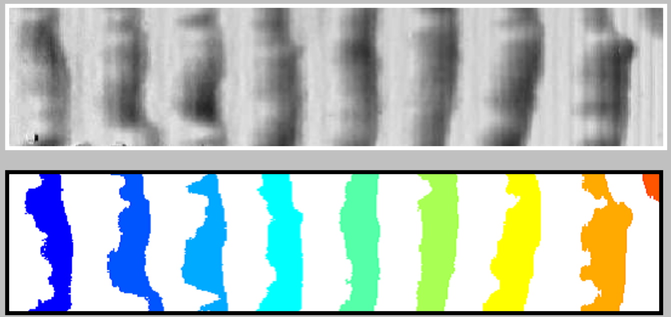
Bedforms and sediment transport in aquatic environments





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Geoflows, KITP - 27 Nov 2013

Selection of bedform morphology in an experimental flume under supply-limited conditions

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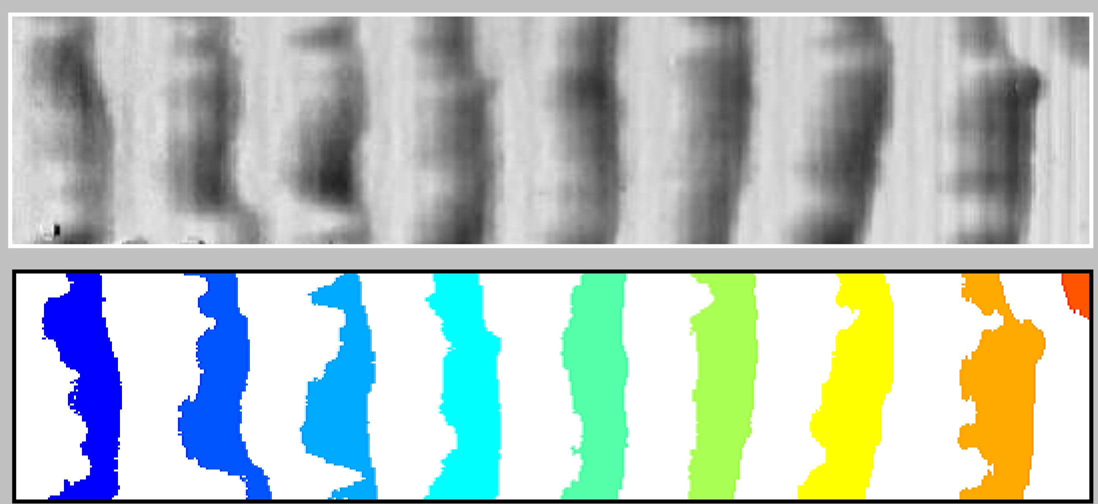
Julie Dréano (PhD thesis), Dimitri Lague, Alexandre Valance



Selection of bedform morphology … : outline

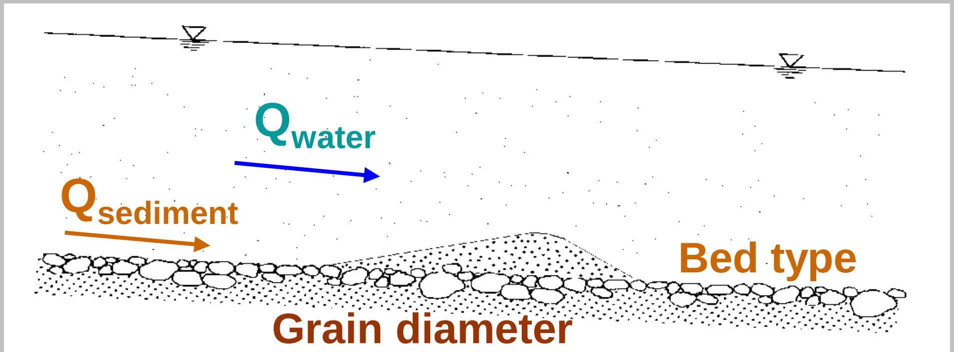
- Motivation

- Experimental set-up, observed morphologies and « 1D » analysis (Dreano *et al*., ESPL, 2010)

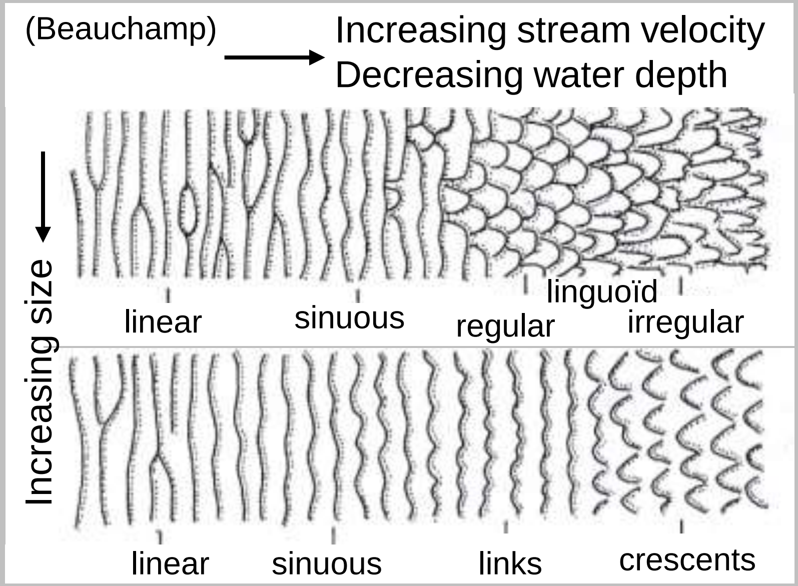
- « 2D » analysis: why, how, sensitivity, power laws

Fluvial sediment transport and bedforms

Control parameters on sediment transport and bedform morphology and dynamics



Shape classification

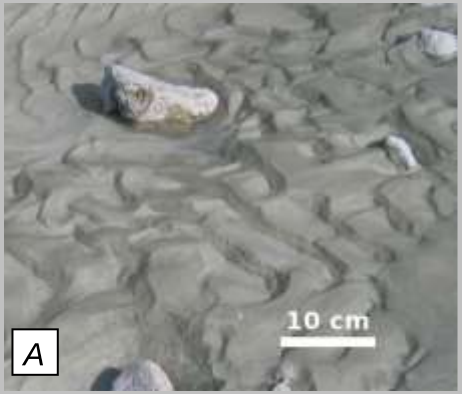


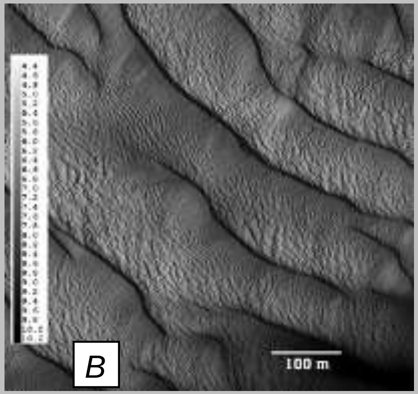
Wide variety of bedforms observed in nature

A. Dunes on dry stream bed at the foot of Otemma glacier

B. Giant dunes, Rio Panamá (Parsons et al. (2005))

C. Bedload sheets, New-Zeland (© Lague)



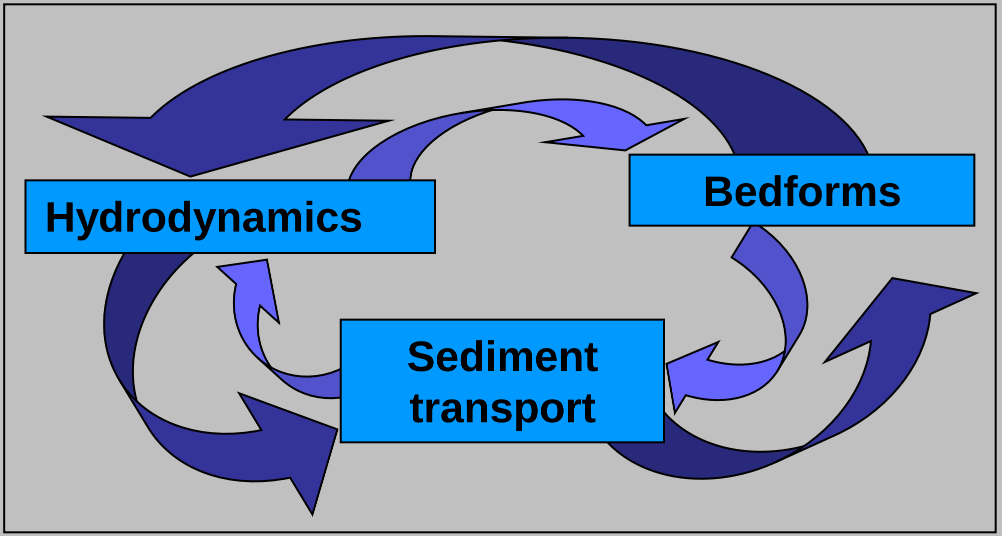


Interacting processes

Bed morphology locally modifies the velocity field: drag from macroscopic roughness, acceleration on crests, boundary layer detachment, recirculation, fluctuations of bed shear stress.

→ Effect on basal shear stress

→ Influence on sediment transport



Experimental results on shear flows over erodible and non-erodible beds

Development of instabilities, **growth** and **saturation** of morphological parameters H and λ (*Langlois (2005), Baas (1999), Mouilleron-Arnould (2002)*, …)

Saturation depending on sediment supply
(Hersen (2004), Noritaka et al. (2005), Tuijnder et al.(2009), …)

Questions

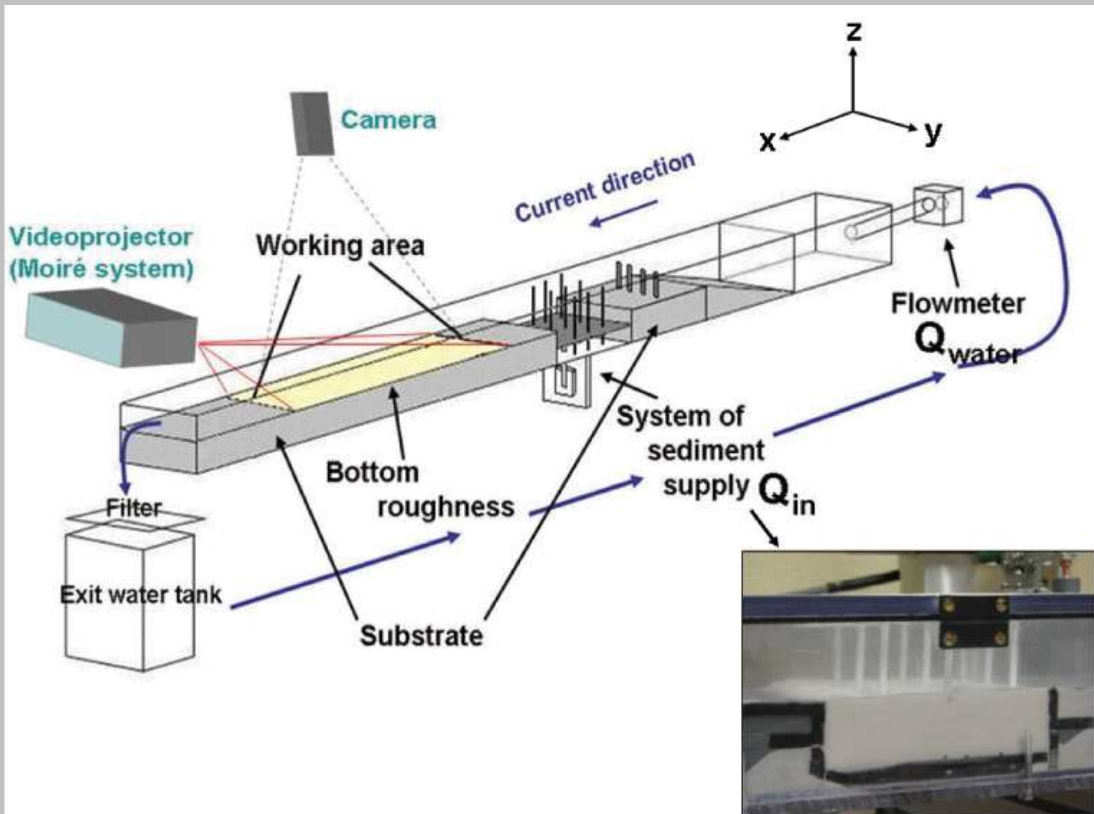
→ What mechanisms are responsible for selection of the morphology and dynamics of dunes?

→ Given an observed morphology, can we invert for the flow and transport conditions typical of bedform formation?

Experimental conditions : 3 parameters (Q_{in}, u*, d)

- Caracterization of the morphology (classification of bedforms)
- Influence of input parameters on bedform development
- Identification of power laws

Set-up characteristics, experimental parameters



- closed-top rectangular duct (3 m long, 120 mm wide and 75 mm deep)
- water depth : 26 to 36 mm
- water circulation with pump
- Water flow rate Q_{water}: 0.82 to 1.25 10^{-3} $m^3.s^{-1}$ (49 to 70 $L.mn^{-1}$)
- Friction velocity u*: 1.6 to 2.5 $cm.s^{-1}$
- Re: 17 to 25 10^3
- sediment flow rate Q_{in}: 6.8 to 121.3 10^{-7} $m^2.s^{-1}$

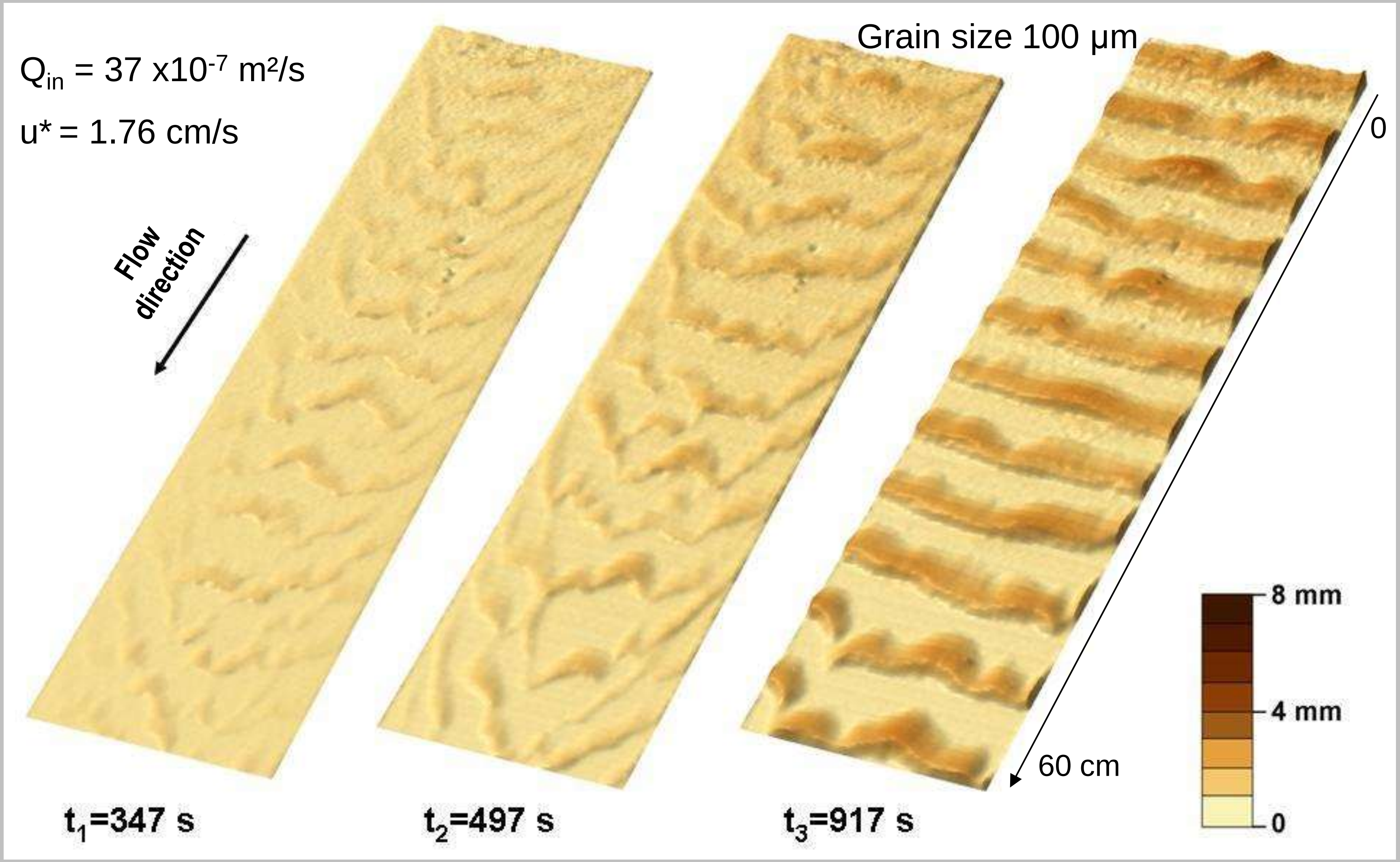
Grain size d	100 µm	500 µm
Rouse	0.8 to 1.3	20.6 to 29.3
Shields	0.18 to 0.35	0.039 to 0.08
Shields_Cr	0.044	0.029
Reynolds_P	1.61 to 2.29	8.46 to 12.04

Controled and limited sediment supply (stepper motor driving supply chamber up)

Flow characteristics: PIV on flat bed, u* evaluated fitting logarithmic velocity profiles

DEM reconstruction of bed morphology: fringe pattern projection (Moiré) (resolution: 1 mm^2, **~ 100 µm** vertical, acquisition time < 3 s, view area L=60 cm)

Example of observed bedforms



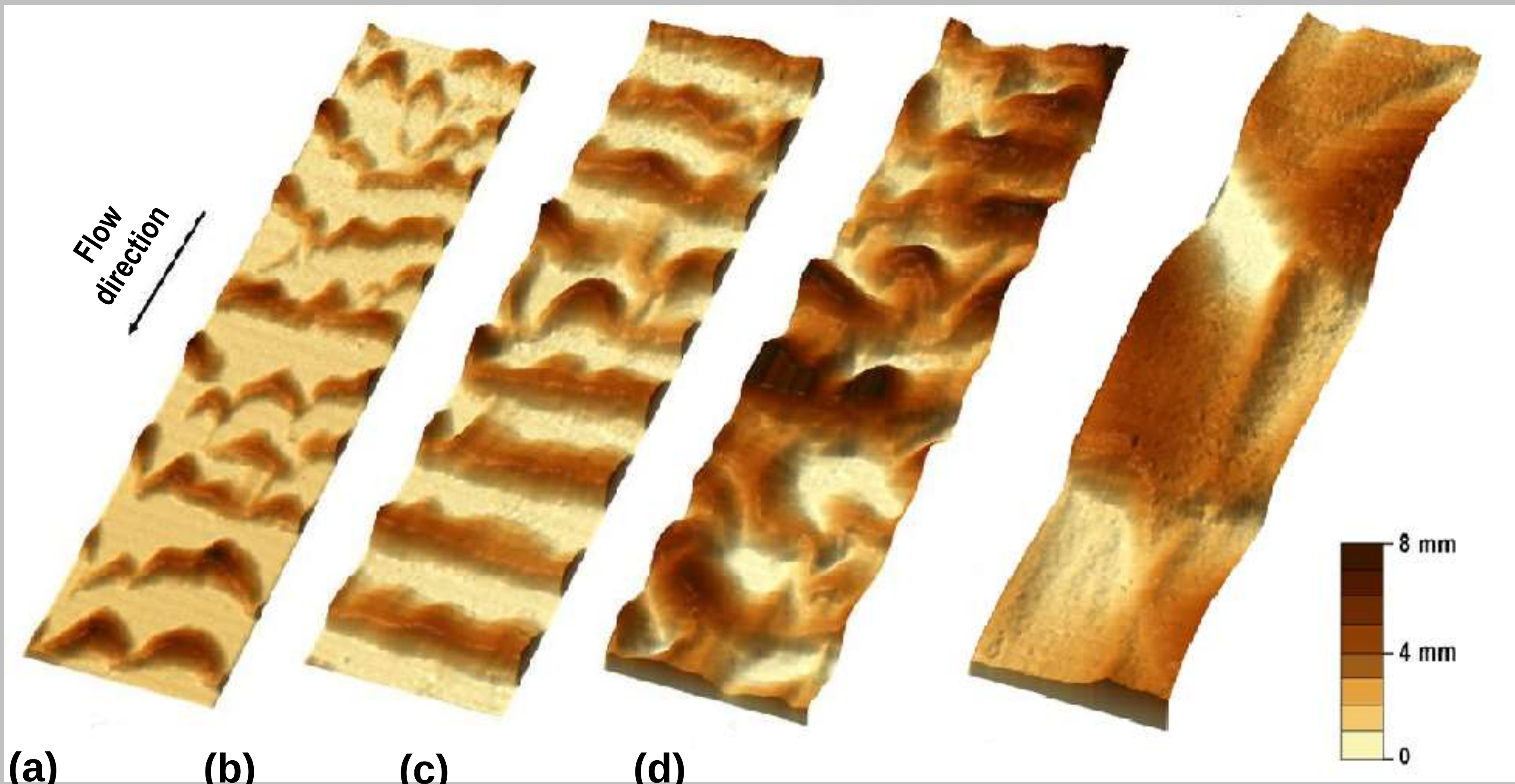
Equilibrium morphologies

Four types of equilibrium
(a) barchan dunes
(b) transverse dunes
(c) linguoïd dunes
(d) bedload sheets

100 μm

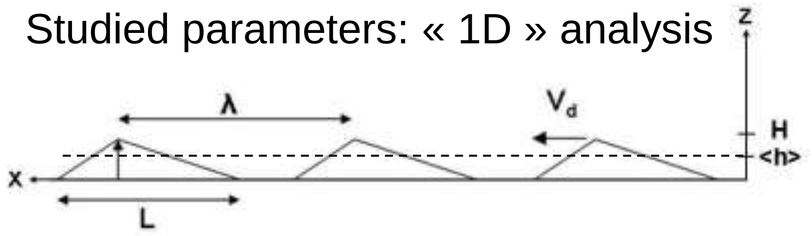
500 μm

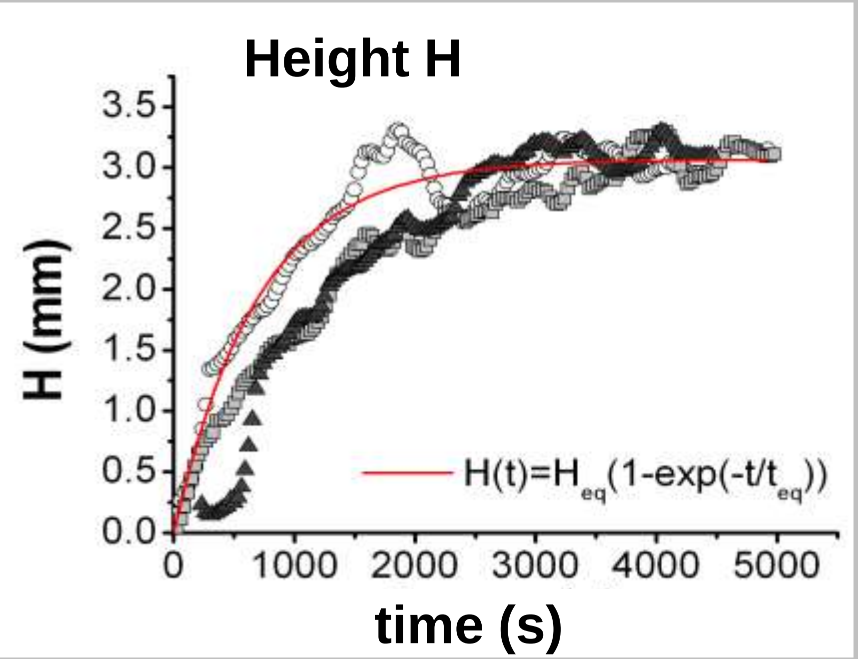
Bedforms tend toward a well-defined, reproducible **steady state** that is **dependent on parameters Q_{in}, u*, d**



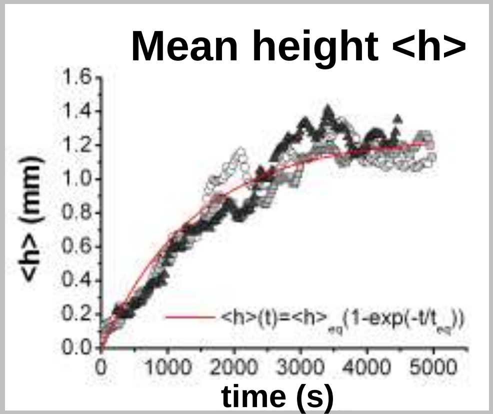
Temporal evolution

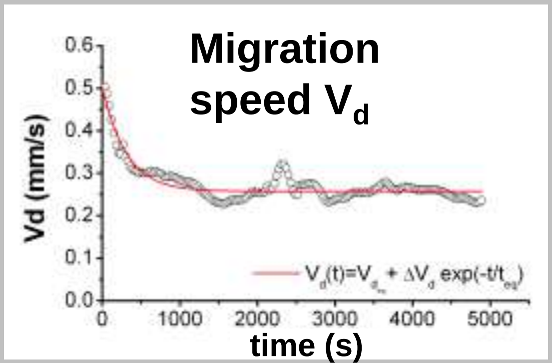
Studied parameters: « 1D » analysis

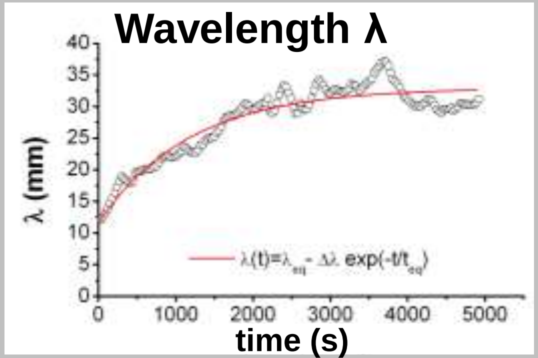




- **100 µm: maturation** then **saturation** of morphological parameters



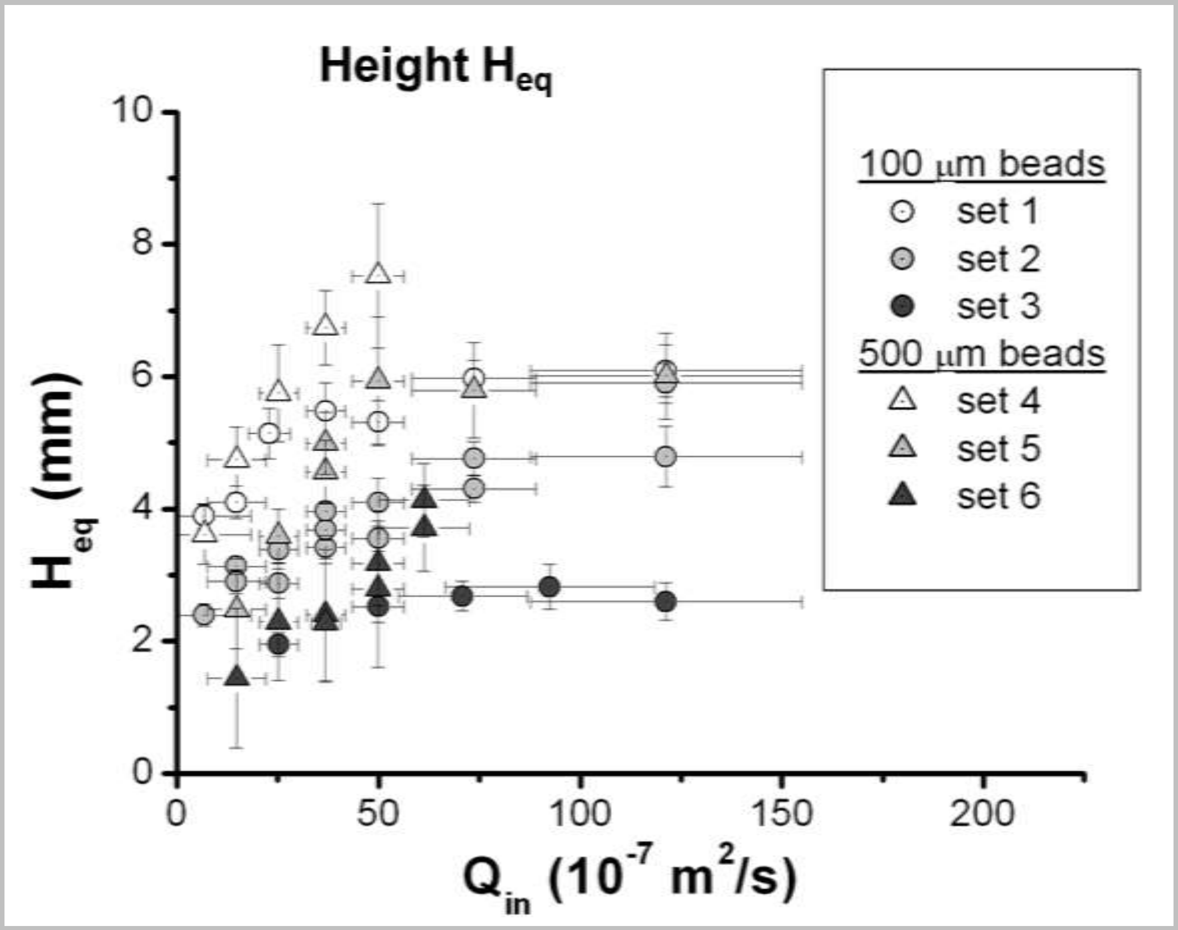




- **500 µm (not shown):** only **saturation**

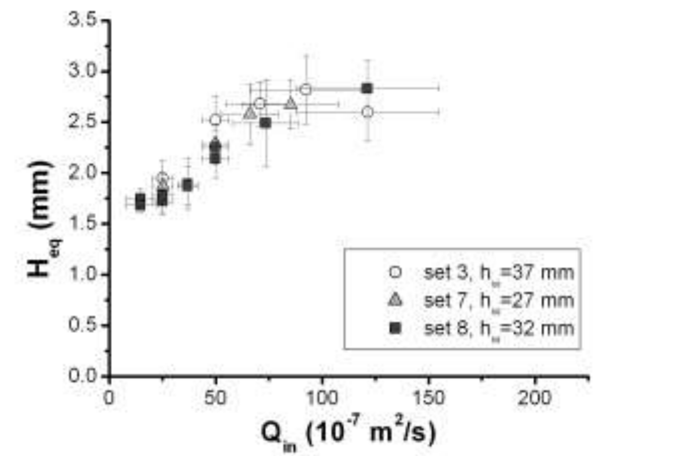
Fluctuations: signature periodic refills of the sediment supply system

Steady state: 2 regimes

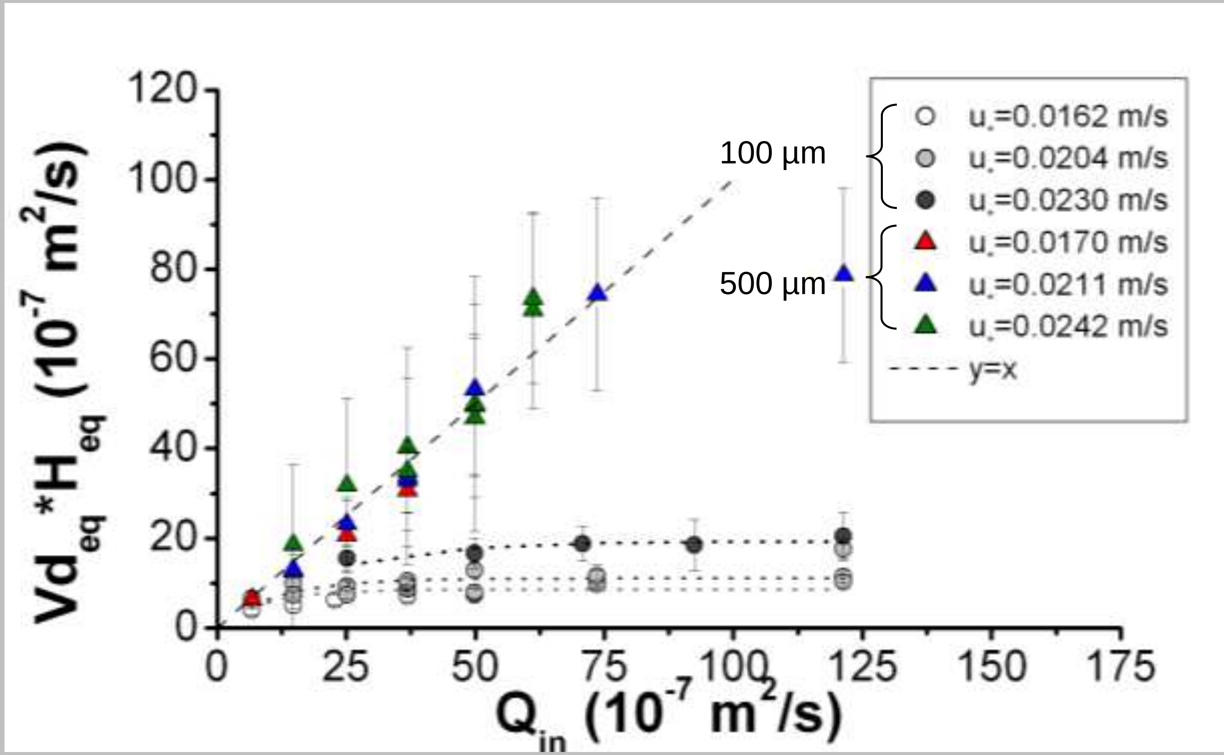


- low Q_{in}: **linear regime**
  - Limited by sediment supply $\mathbf{Q_{in}}$
- high Q_{in}: **saturated regime**
  - Not reached with 500 µm grains
  - Limited by bedload transport (maximum transport capacity of the flow)

Influence of water depth



Steady state: 2 modes of transport



Transport modes

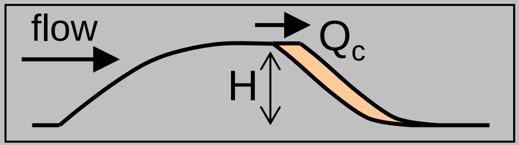
- 100 µm: bedload and suspension
- 500 µm: bedload only

→ **Q_c** relevant sediment flow rate for phase diagram

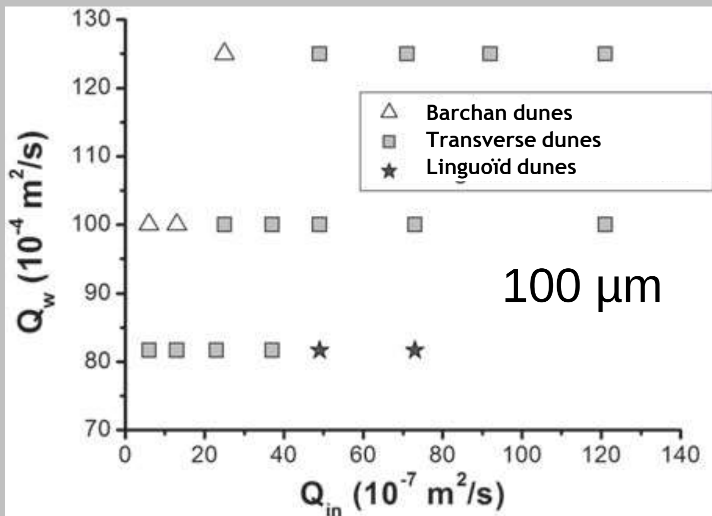
$$\boxed{Q_c = V_{deq} \times H_{eq}}$$

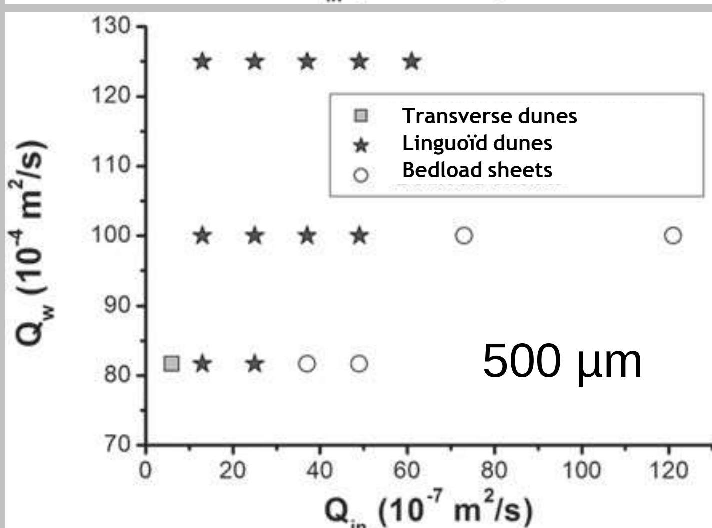
- **100 µm** grain size
  Q_c saturation
  Q_{susp} dominant

- **500 µm** grain size
  V_{deq} x H_{eq} (=Q_c) ≈ Q_{in}
  Q_{susp} ≈ 0



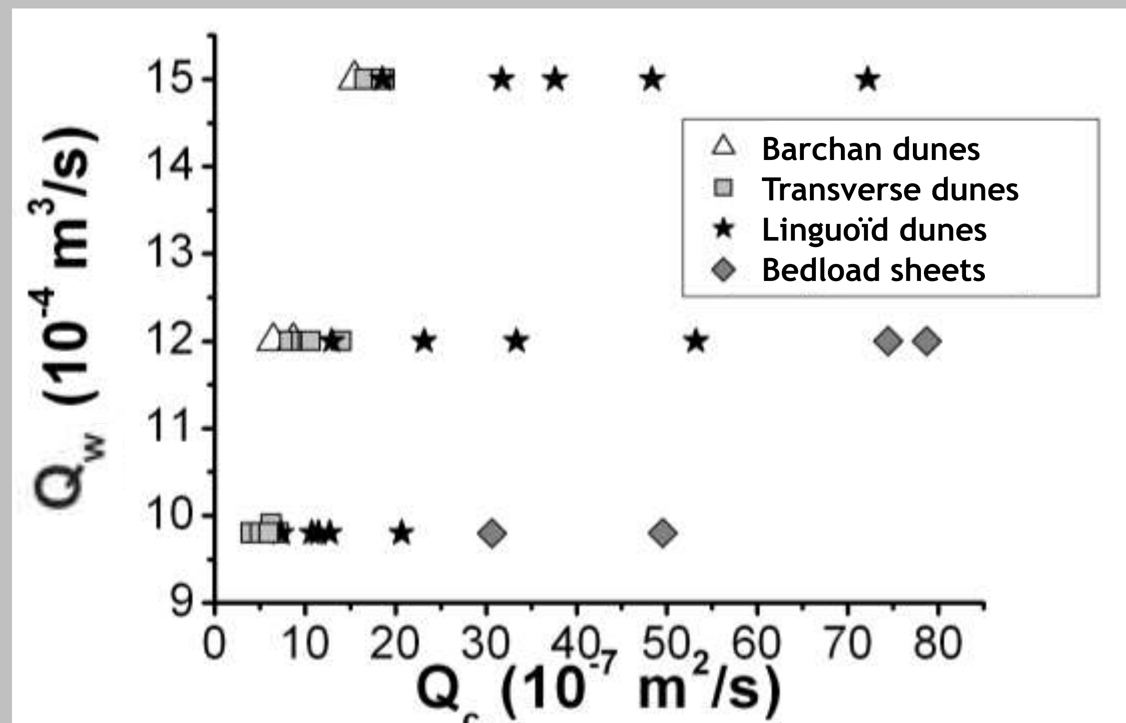
Phase diagrams





Input parameter domain for each grain size

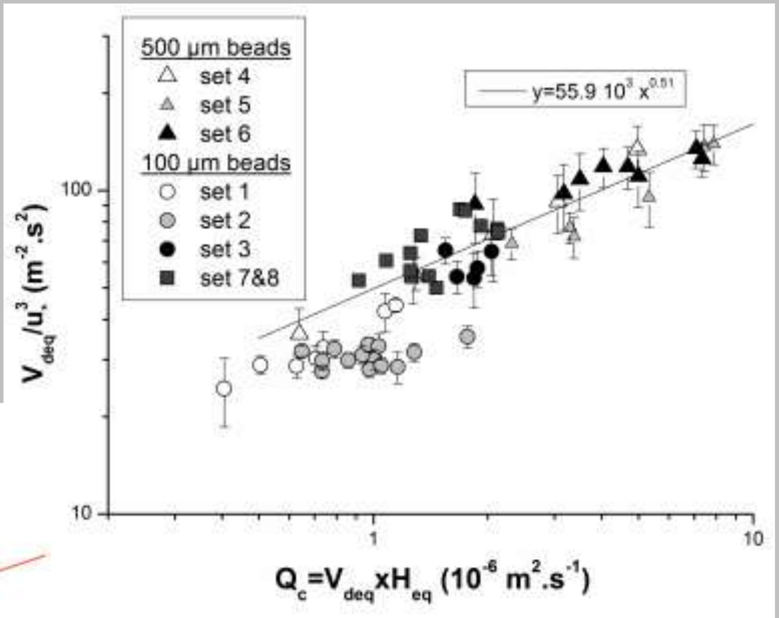
Both grain sizes together using the sediment flux Q_c

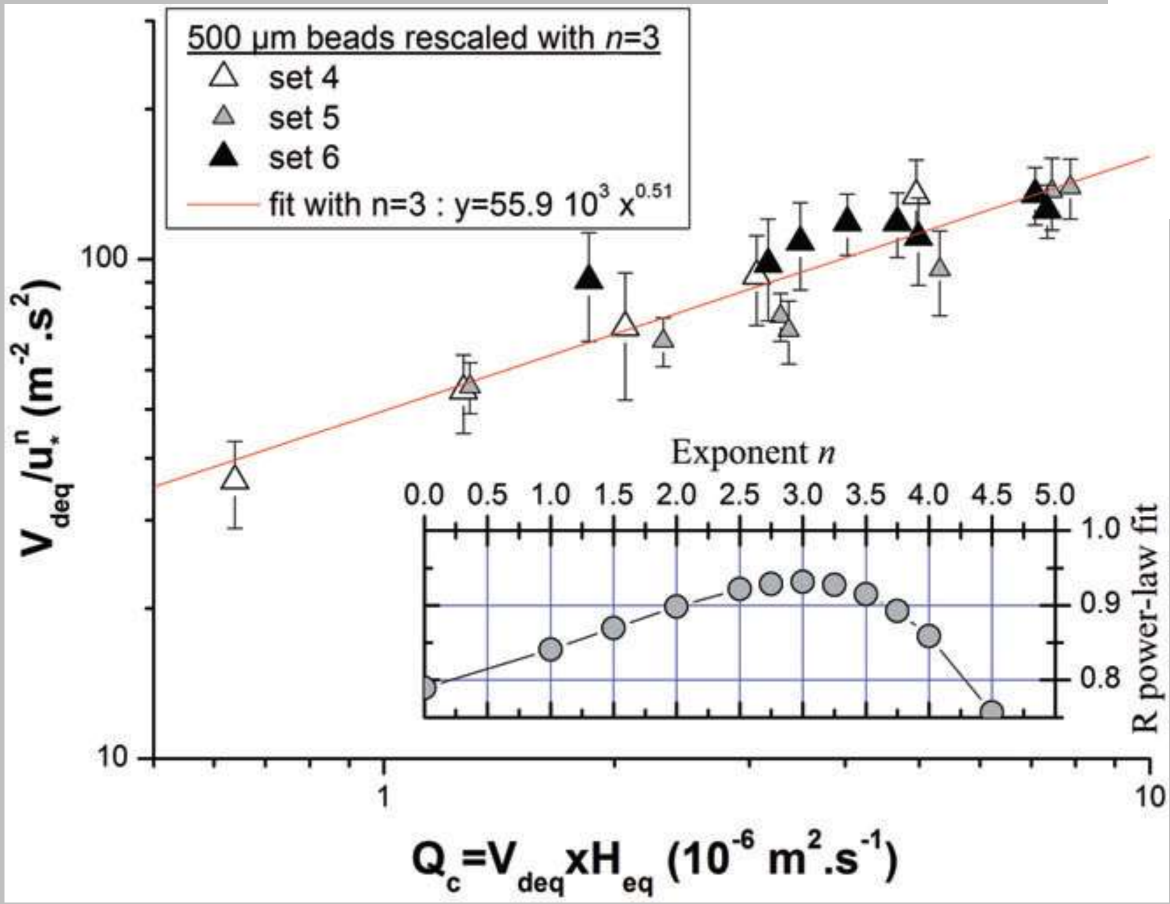


Power laws

$$V_{eq} = k\, u_*^3\, Q_c^{0.5}$$

Scaling not readily explained





Applicable to bedforms of diverse shapes (for 500 µm, essentially bedload)

Not followed by 100 µm grains … different transport modes

Motivation for « 2D » analysis

Limitations of « 1D » analysis (morphological parameters computed on streamwise bed profiles, spanwise averaging):

- incomplete exploitation of dataset (spanwise variability, pattern organization)
- inadapted to bedforms not aligned with flow (obliquity, sinuosity)

« 2D » approach: identification of sedimentary structures as objects (**image segmentation** with a threshold applied to the topography and **object analysis** on the resulting binary images)

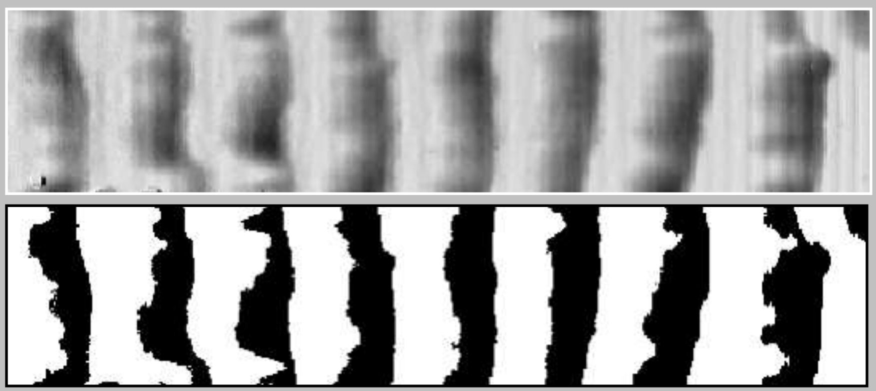
- better accounts for bedform complexity (heterogeneity, variability)
- access to additional parameters: curvature, tortuosity
- unbiased verification of visual classification
- possibility to track bedforms (morphodynamics)

Objective: identify parameters interpretable in terms of near bed hydrodynamic processes to relate morphology to sediment transport

Method: threshold on grayscale images

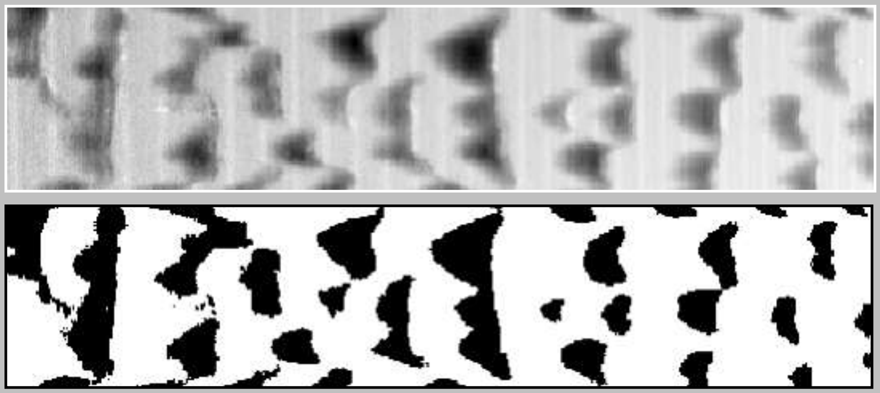
Threshold determination : minimum intra-class variance of black and white pixels

Transverse dunes

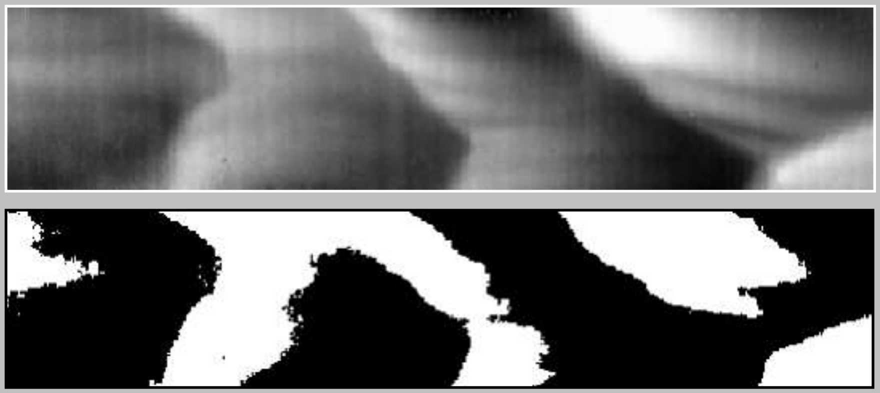


Linguoïd dunes

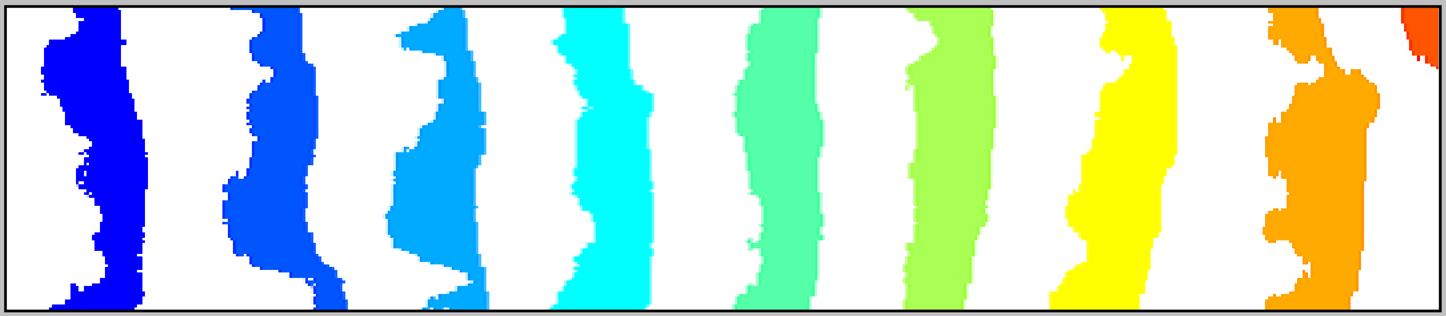
Barchanes



Bedload sheets



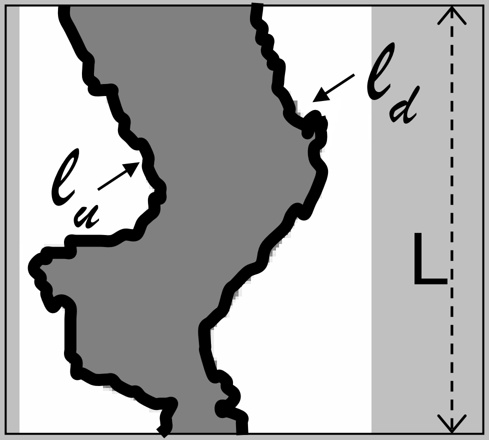
Morphological parameters



- Number of bedforms per image
- Sinuosity: ratio of contour length to double width of bedforms
- Area ratio of bedform regions to entire image size
- Others: continuity across image

…

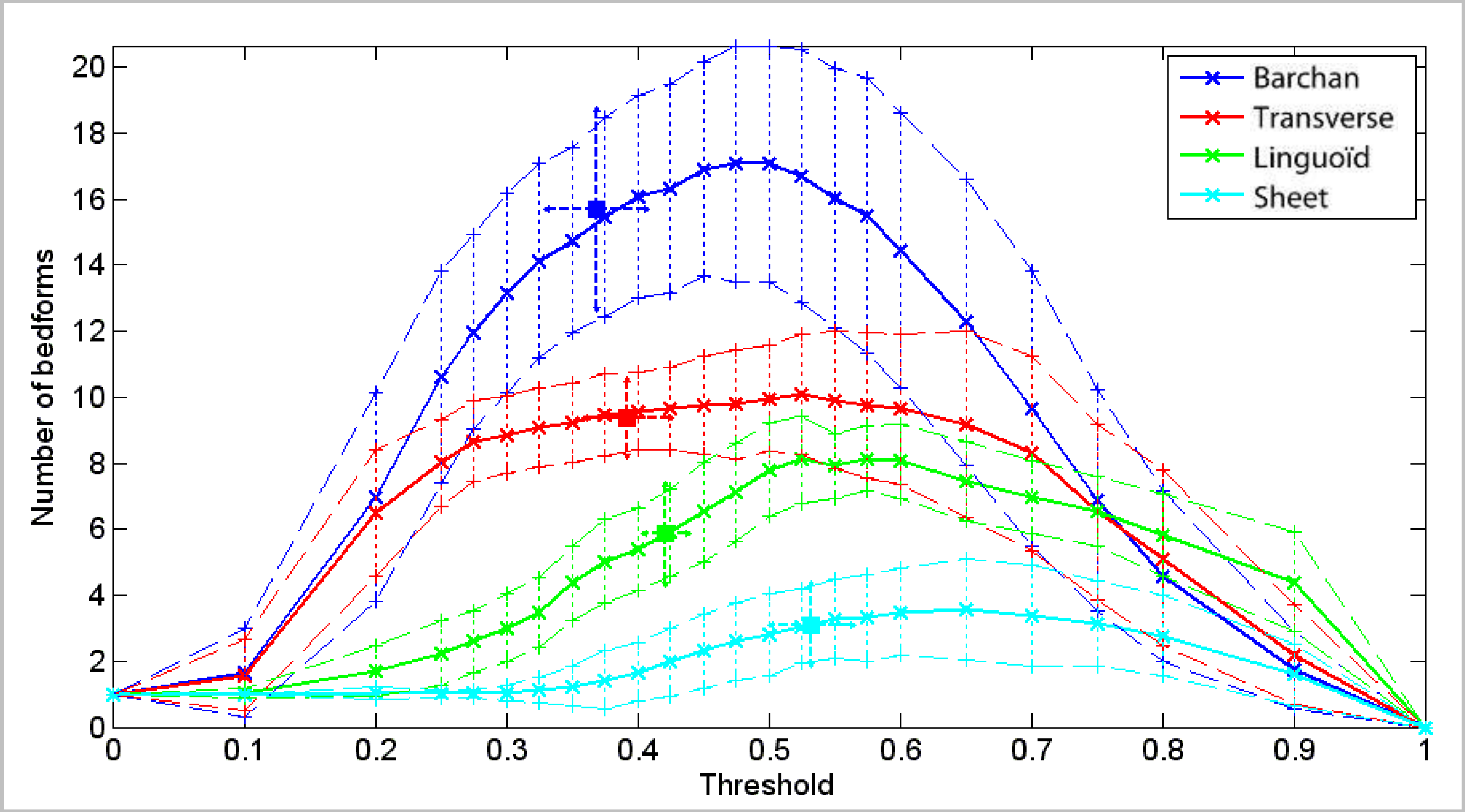
$$S = \frac{\ell_u + \ell_d}{2\,L}$$



Assess their properties: variability (sensitivity), bedform discrimination

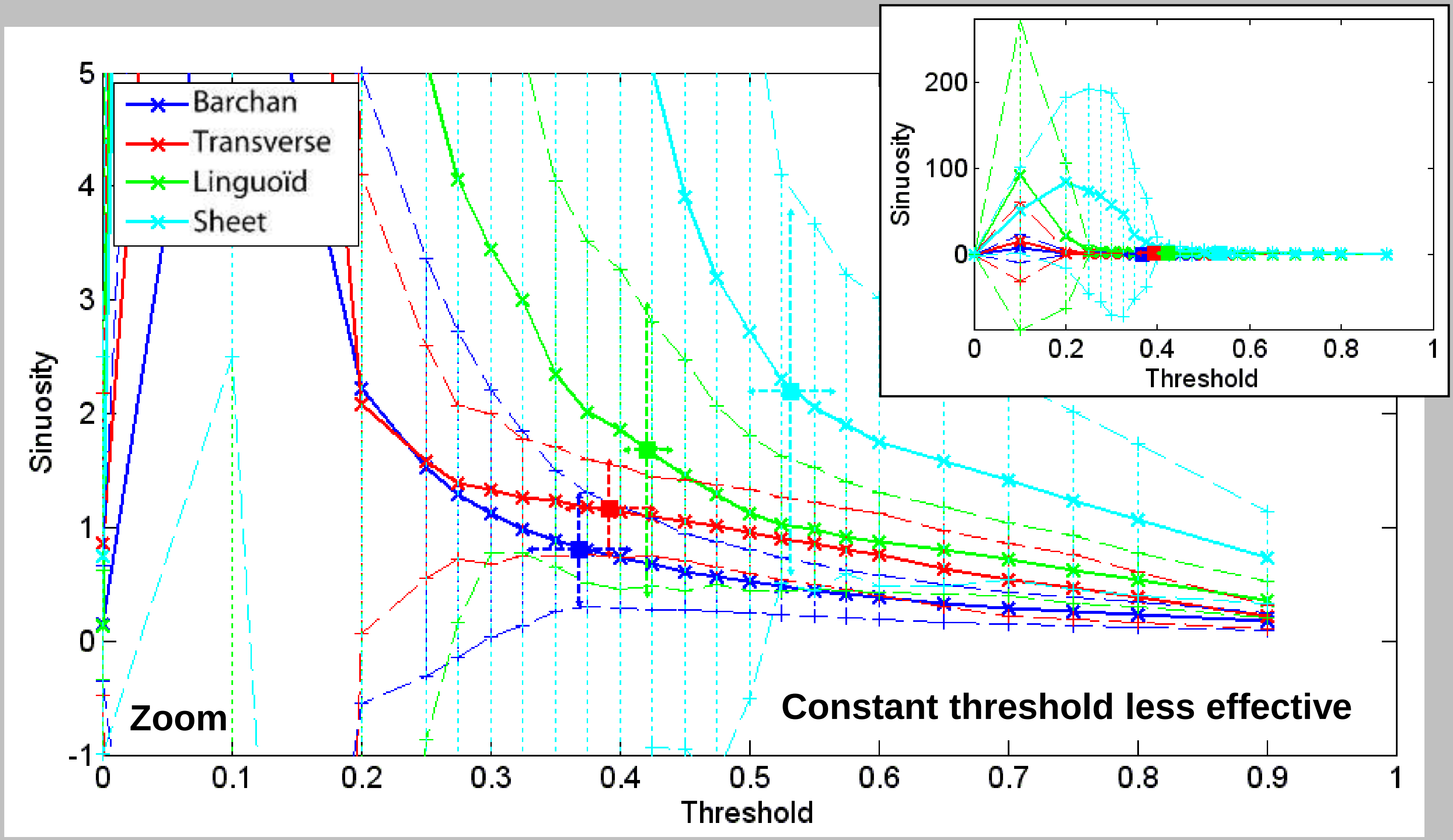
Best way to select the threshold so as to optimize discrimination?

Bedform count



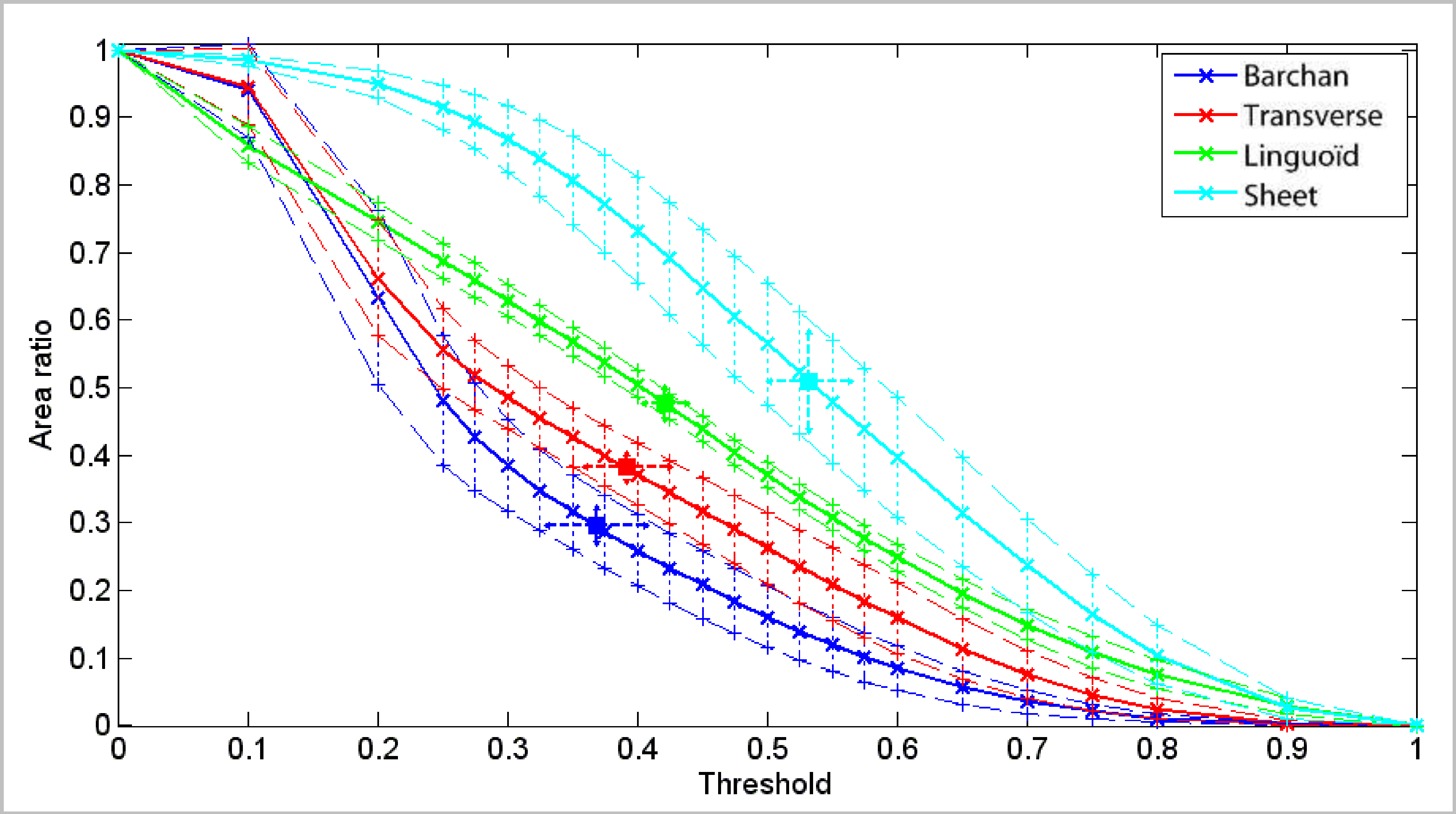
- discriminant parameter
- stable over a wide range of thresholds

Sinuosity



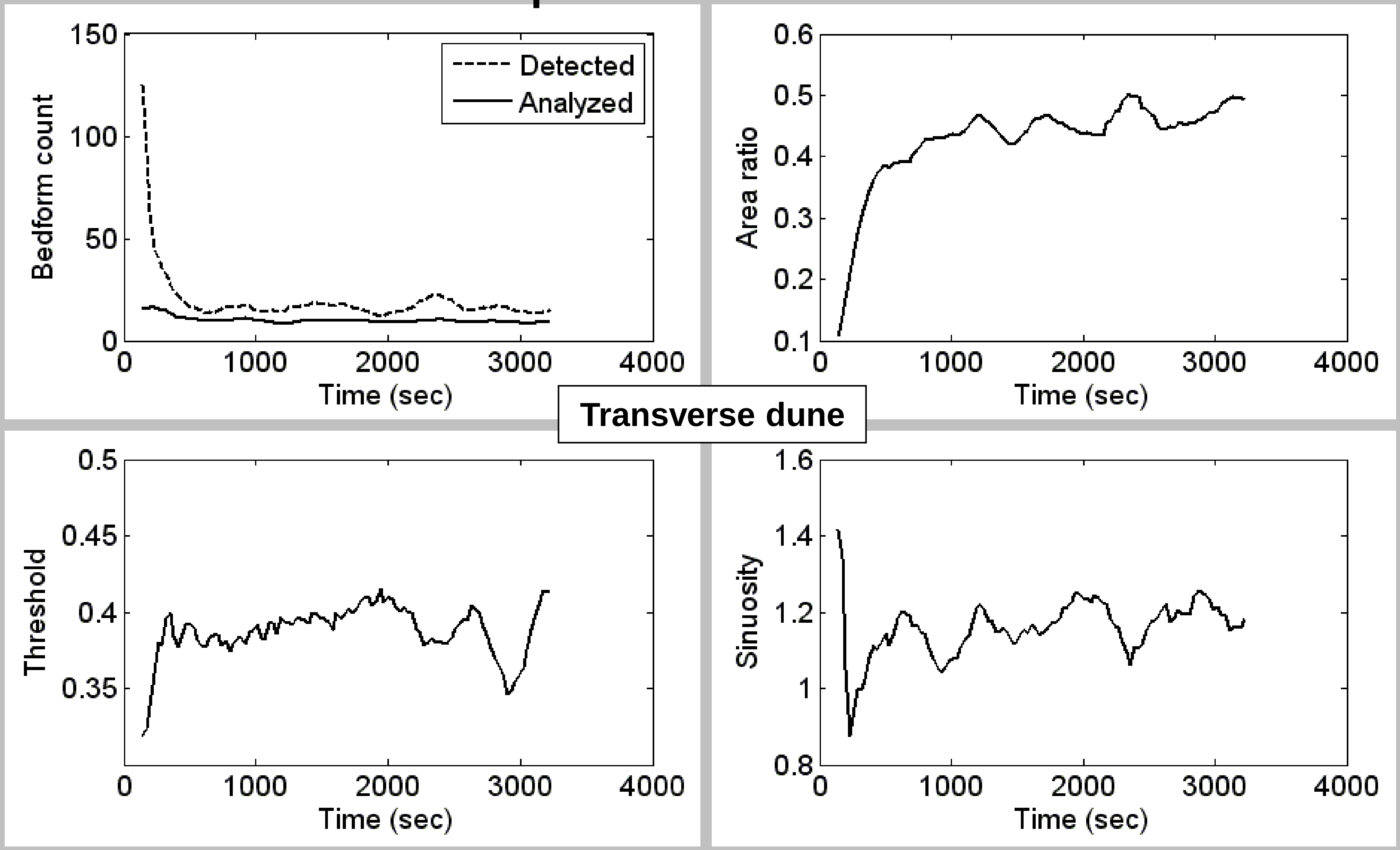
- stable except for low thresholds
- need to handle truncated bedforms

Area ratio



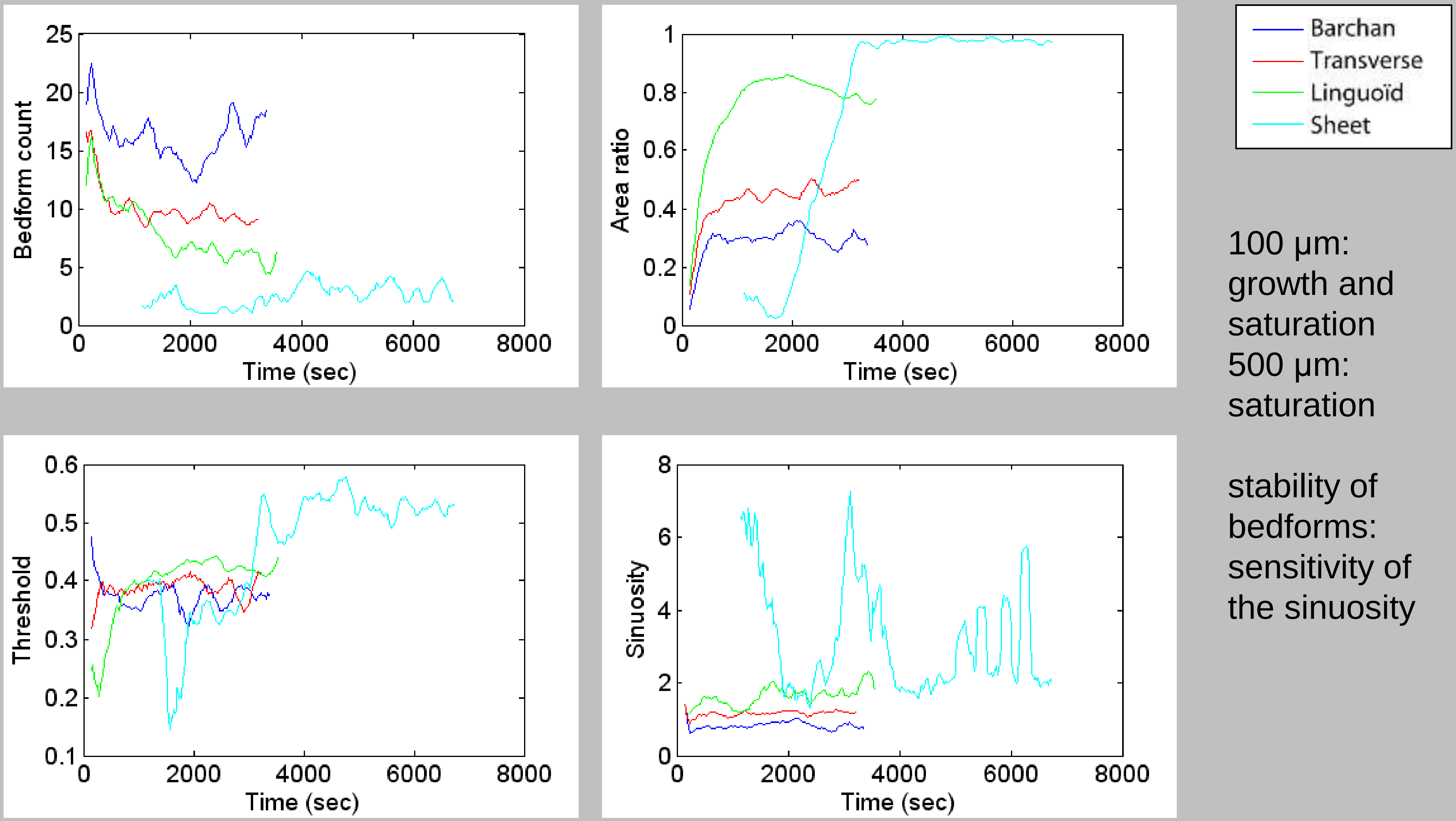
- Low standard deviation
- Horizontal scans of the topography

Temporal evolution



- growth followed by saturation
- effect of supply reload
- stability of bedforms

Temporal evolution



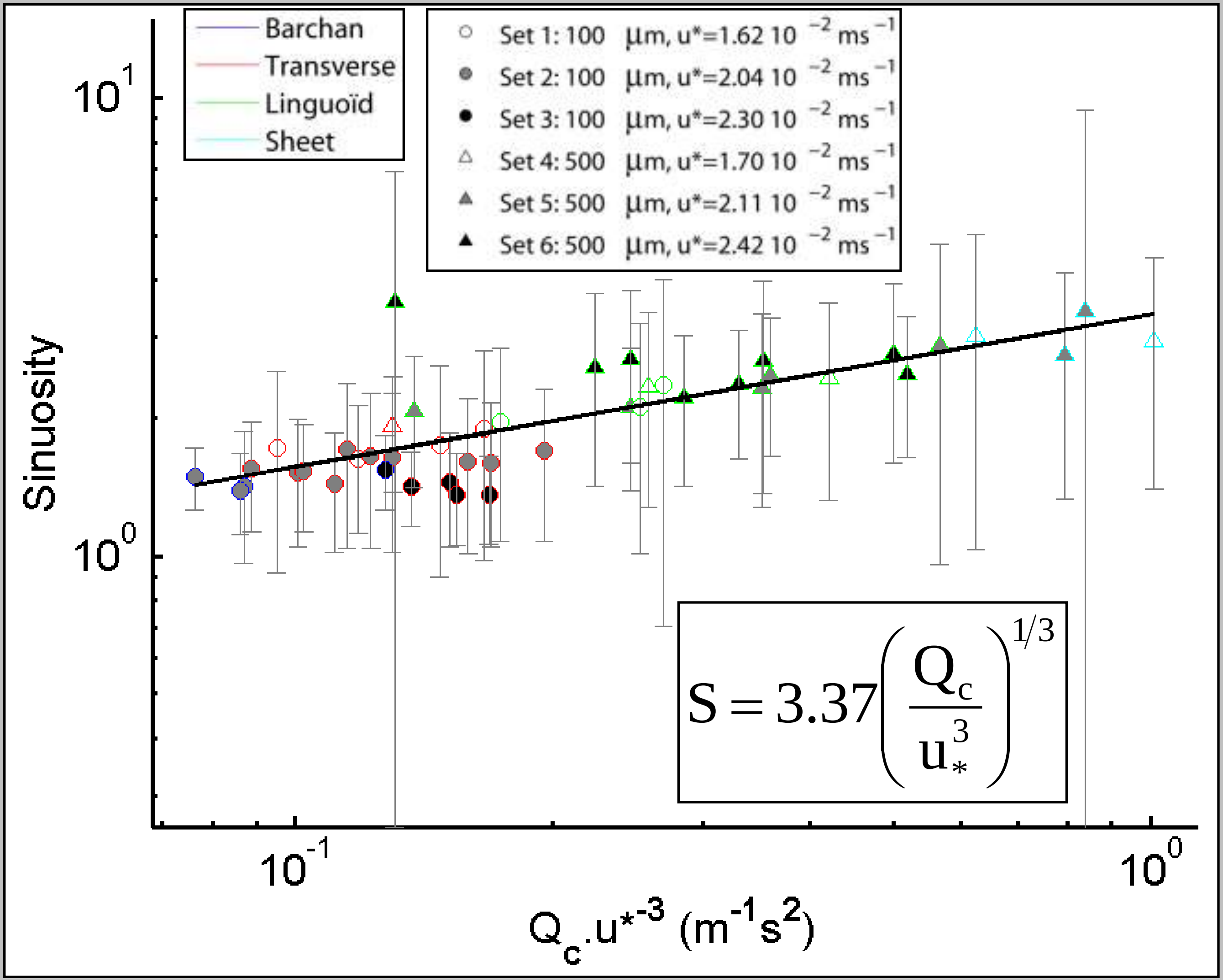
100 µm: growth and saturation
500 µm: saturation

stability of bedforms: sensitivity of the sinuosity

Power law using the sinuosity

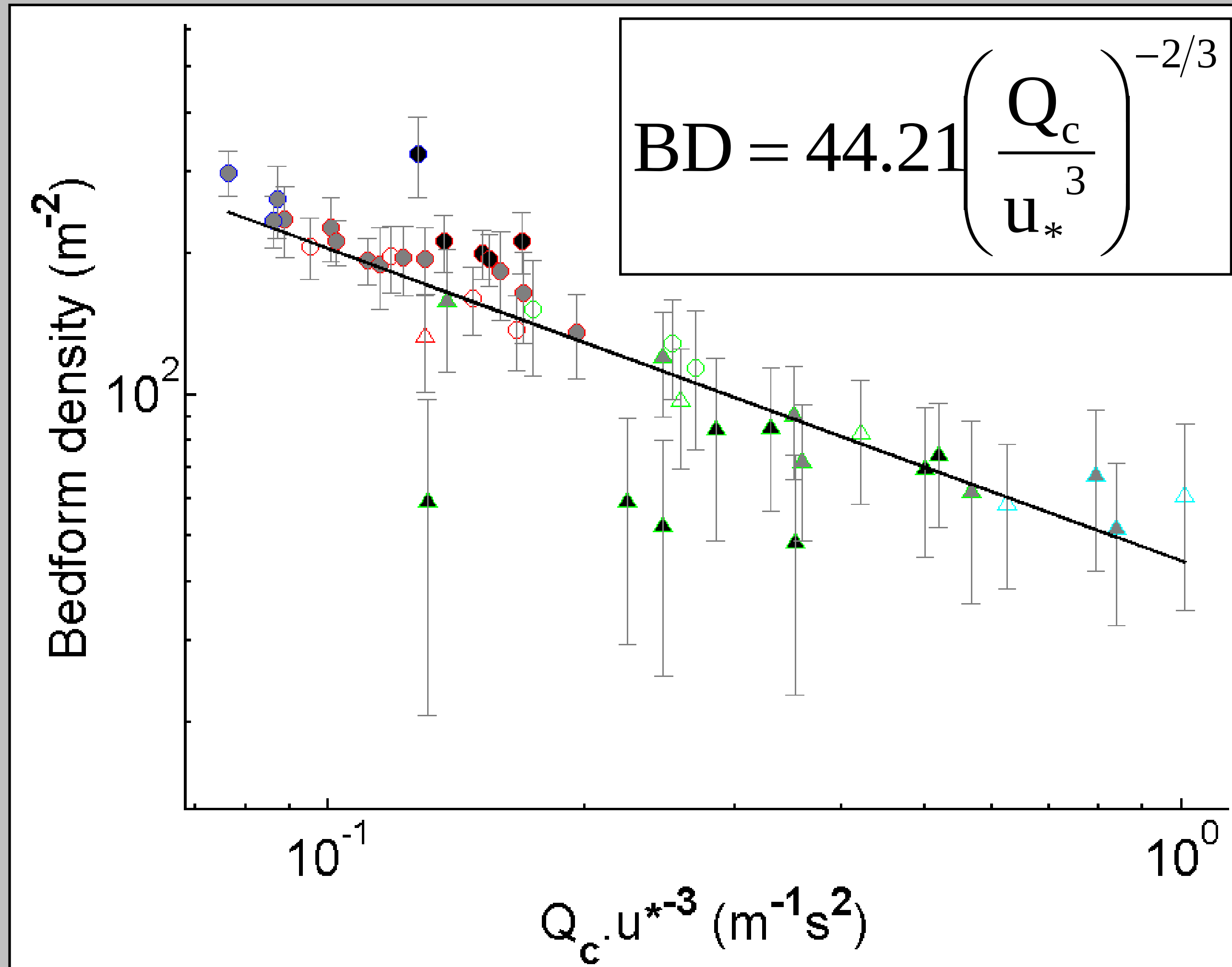
- Convincing scaling valid for all confirgurations tested:
  - relevance of sinuosity to characterize the bedforms.

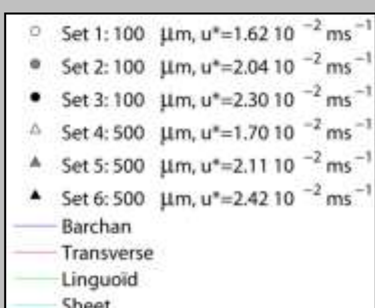
- Physical interpretation on the role of hydrodynamical processes in the selection of morphologies ?
  - relationship between sinuosity and transverse instability



Power law using bedform density

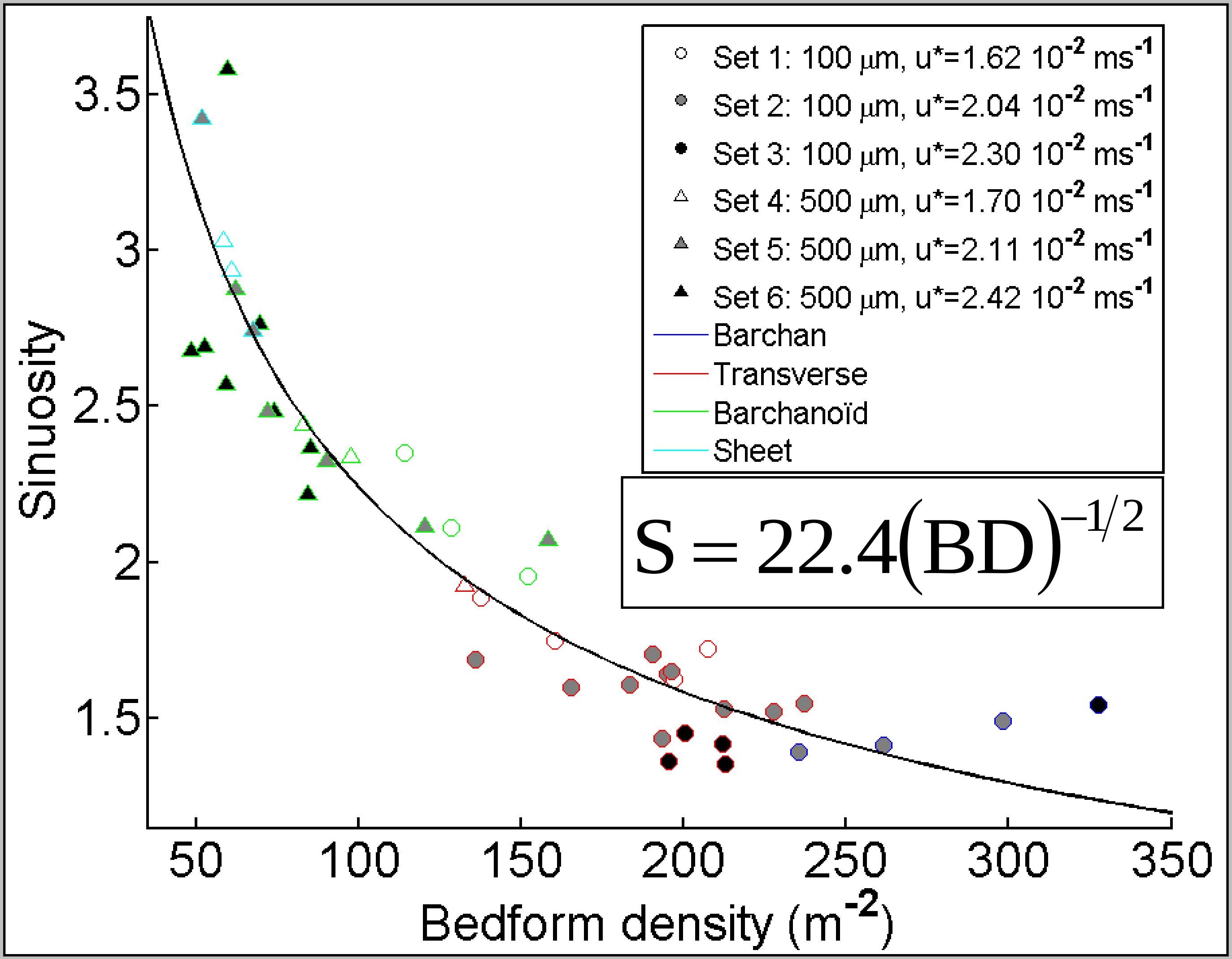
• Relevance of bedform density as an indicator on the forcing conditions:
- typical wavelength for transverse bedforms.
- paving and staggering for barchanes.
- bedform continuity (coverage) for linguoid dunes (bedload sheets).
- link to coalescence dynamics (coarsening) ?





Bedform shape classification

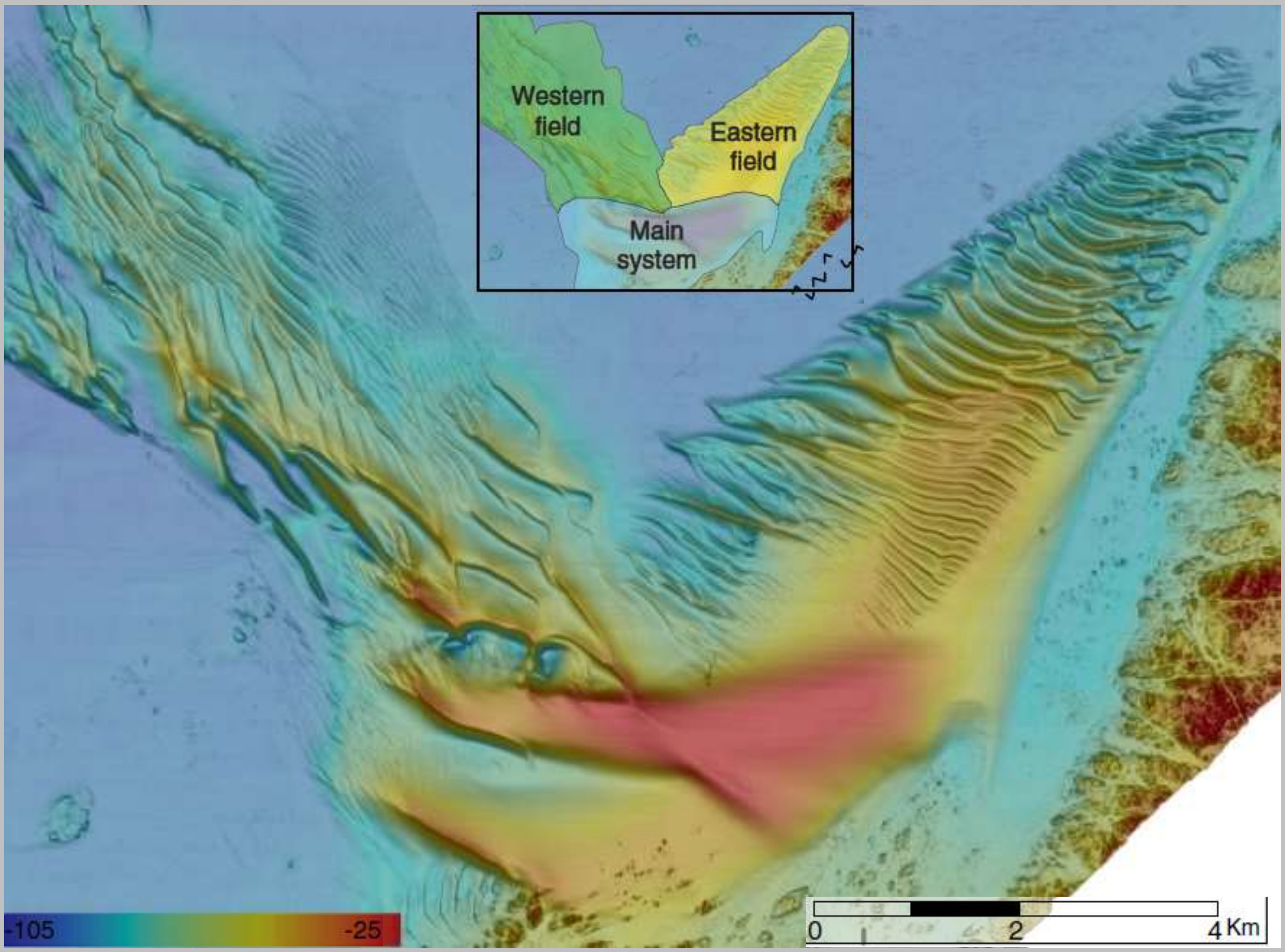
- Pair of parameters effective to discriminate bedform morphlogies.
- Only 1 independent parameter (same power dependence): more needed to invert for forcing conditions.



Perspectives

- Effect of a free-surface
- Validity of the proposed scaling laws on field data
- Relationships between morphology and forcing parameters
  - interpretation of Q_c with respect to sediment flow rate
  - influence of sinuosity on velocity field at dune scale
  - effect on bedform staggering on velocity field at dune field scale
- Further exploitation of DEM
  - refine threshold selection
  - additional parameters (singularities, …)
  - analysis of « 3D » objects (curvature, volume geometry)
  - bedform tracking: morphodynamics

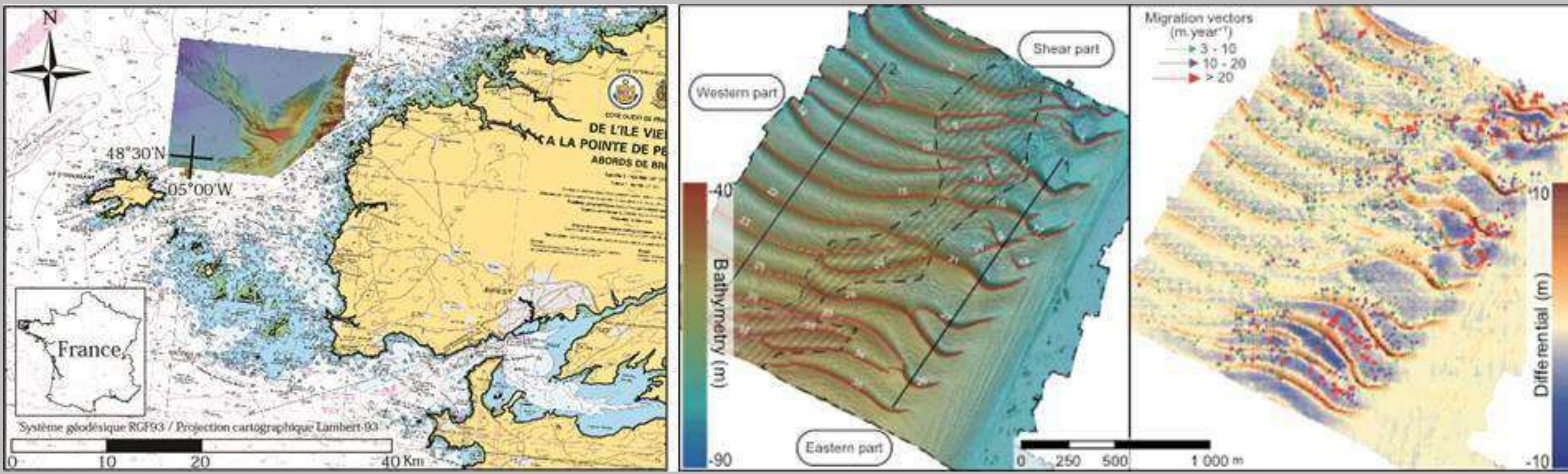
Dynamics of large submarine dunes



Franzetti *et al.*, Mar. Geol. 2013

Nicolas
Le Dantec,
France
Floc'h, …

Study site: le « Banc du Four »

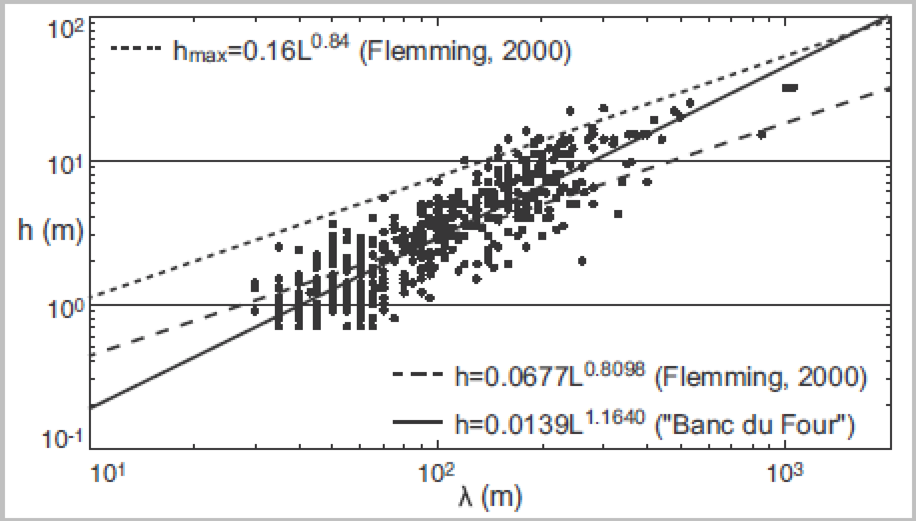


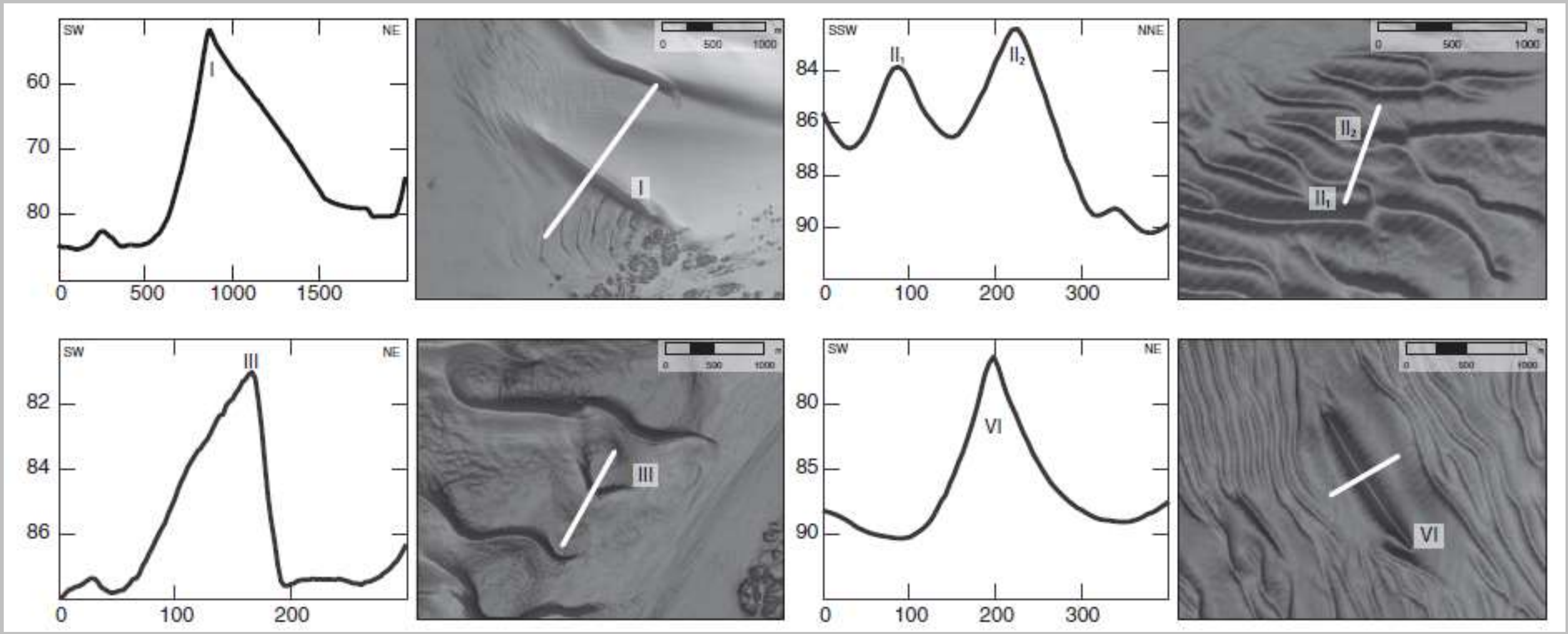
- large variety in dune shape and size (0.2 < H < 30m, 10 < L < 1000m)
- displacements up to 20 m/year (indication of morphodynamical equilibrium?)
- macrotidal regime with intense residual currents and Atlantic storms
- large spectrum of hydrodynamic forcing conditions (context, Ouessant tidal front)

Unique history of formation of the dune field during last marine transgression:
- relict depocenter (organogenic debris with a mean grain size of about 0.8 to 0.9 mm)
- successive openings of two sills yielding distinct successive regimes of currents
- resulting changes in the dune dynamics over historical times visible in seismic record

Dune characteristics

- good height-spacing correlation but the regression observed in prior studies
- No clear relationship between size parameters asymmetry and, nor between dune migration rates and dune size





Proposed work

Exploit multitemporal series on evolution and mobility of large submarine sand dunes to address the up-scaling problem by measuring dune-scale transport processes together with their field-scale signature
- respective contributions of bedload and suspended load to bedform migration
- controls on wavelength selection and pattern emergence (inter-dunes dynamics)
- effect of highly energetic vs cyclic events (storms, tides, wave climate)

•**high-resolution measurements of instantaneous, small-scale sediment processes** (microbathymetry, near-bed velocity and sediment concentration, continuous monitoring of dune front dynamics)
•**larger-scale 4D observations and model predictions of present and past dynamics of the dune field and of hydrodynamic forcing** (morphological analysis of bedform from multitemporal bathymetry, measurement and modeling of mesoscale hydrodynamics, past dynamics from internal dune stratigraphy)
•**integrate multiple scales of representation of dune dynamics** (correlations and power laws, stability analyses, statistical methods with transfer functions)

Morphology of pillow-hollow and quilted-cover bedforms in Lake Geneva, Switzerland

Nicolas Le Dantec, Yosef Akhtman, Dragos Constantin, Ulrich Lemmin, D.A. Barry, Oscar Pizarro, Samuel Arey, Richard Camilli, Angelos Mallios

elemo
exploration des eaux lémaniques

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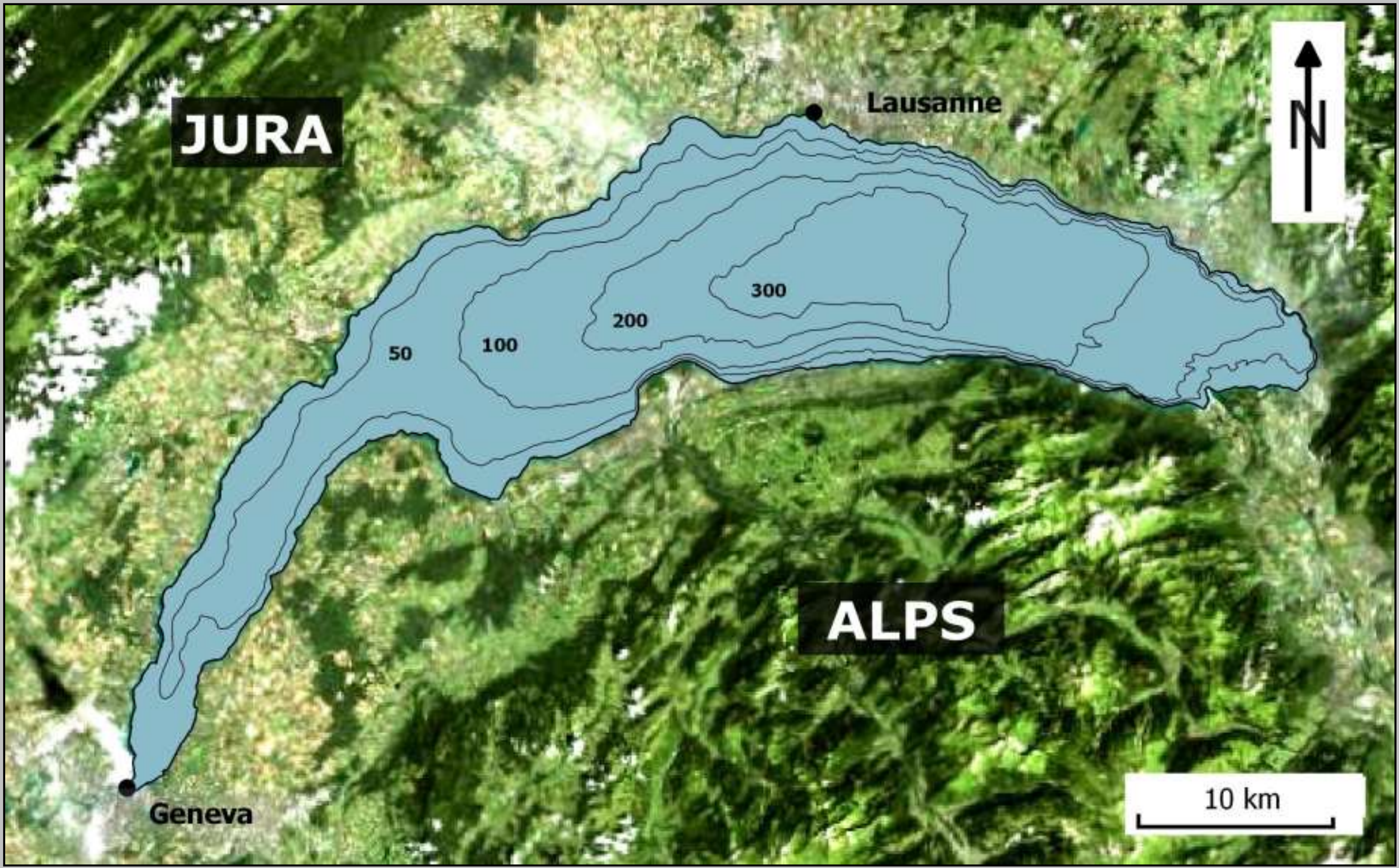
cetmef

… bedforms in Lake Geneva : outline

- Context and methods
- Classification, distribution and 3D models
- Formation mechanism?

Lake Geneva



MIR submersibles

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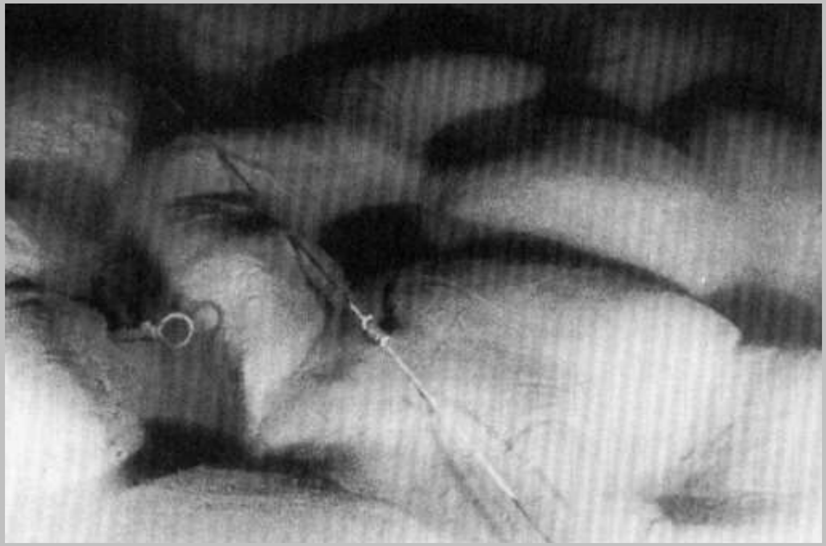
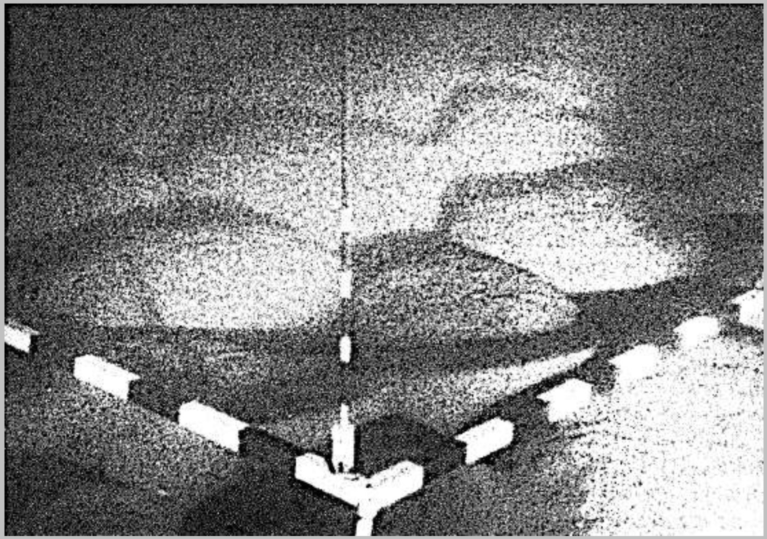
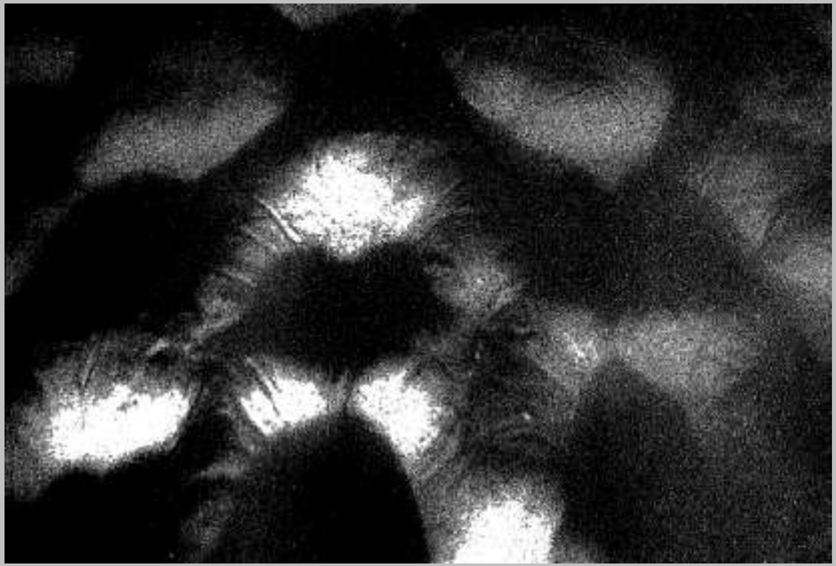
exploration des eaux lémaniques

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE ©Alain Herzog/EPFL

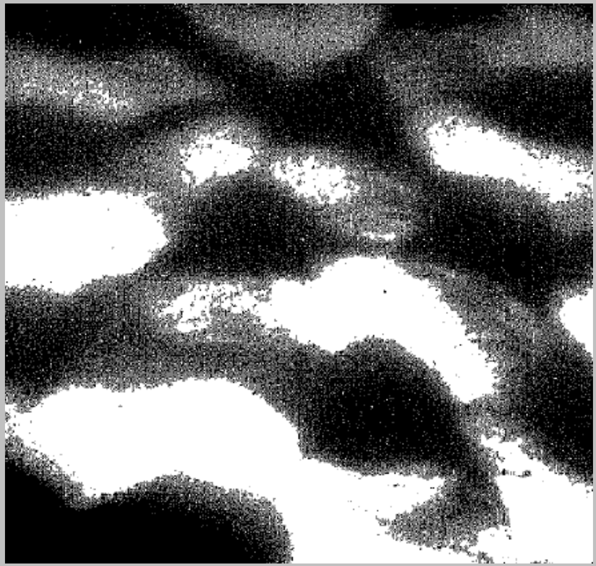
Prior reports on lake-bottom bedforms



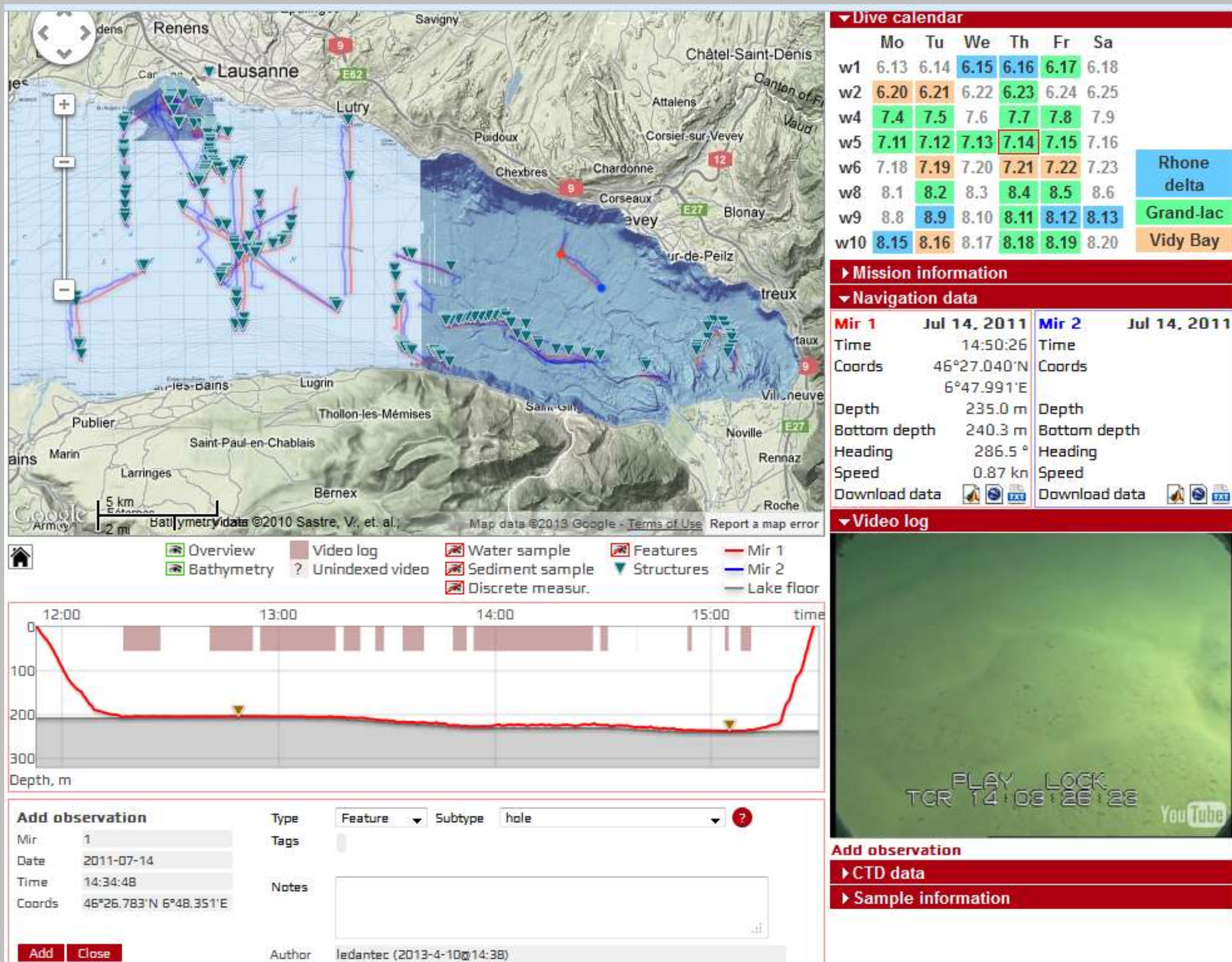




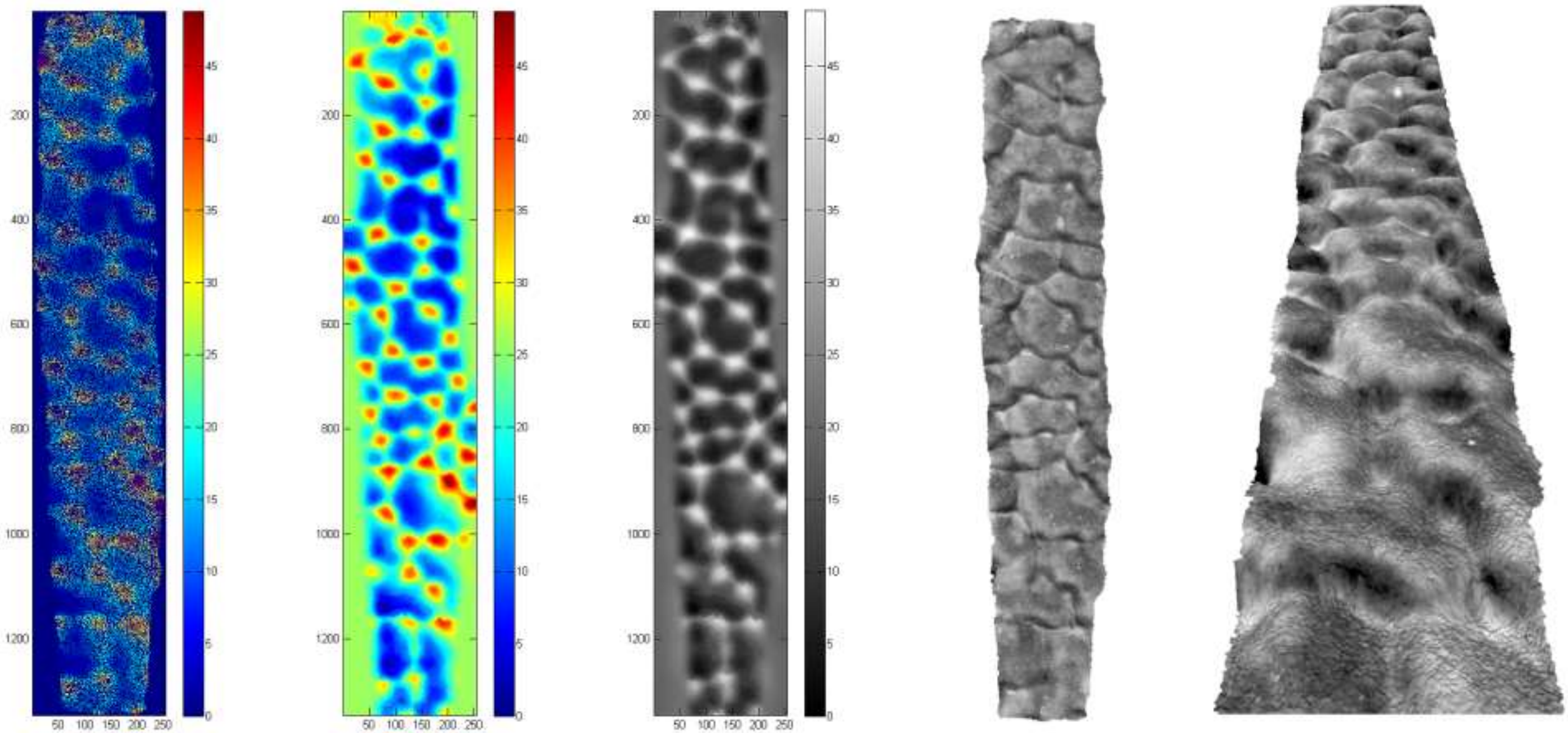
Vernet 1966, Brandl *et al.* 1993, Dominik *et al.* 1992 (Piccard and Forel submersibles)



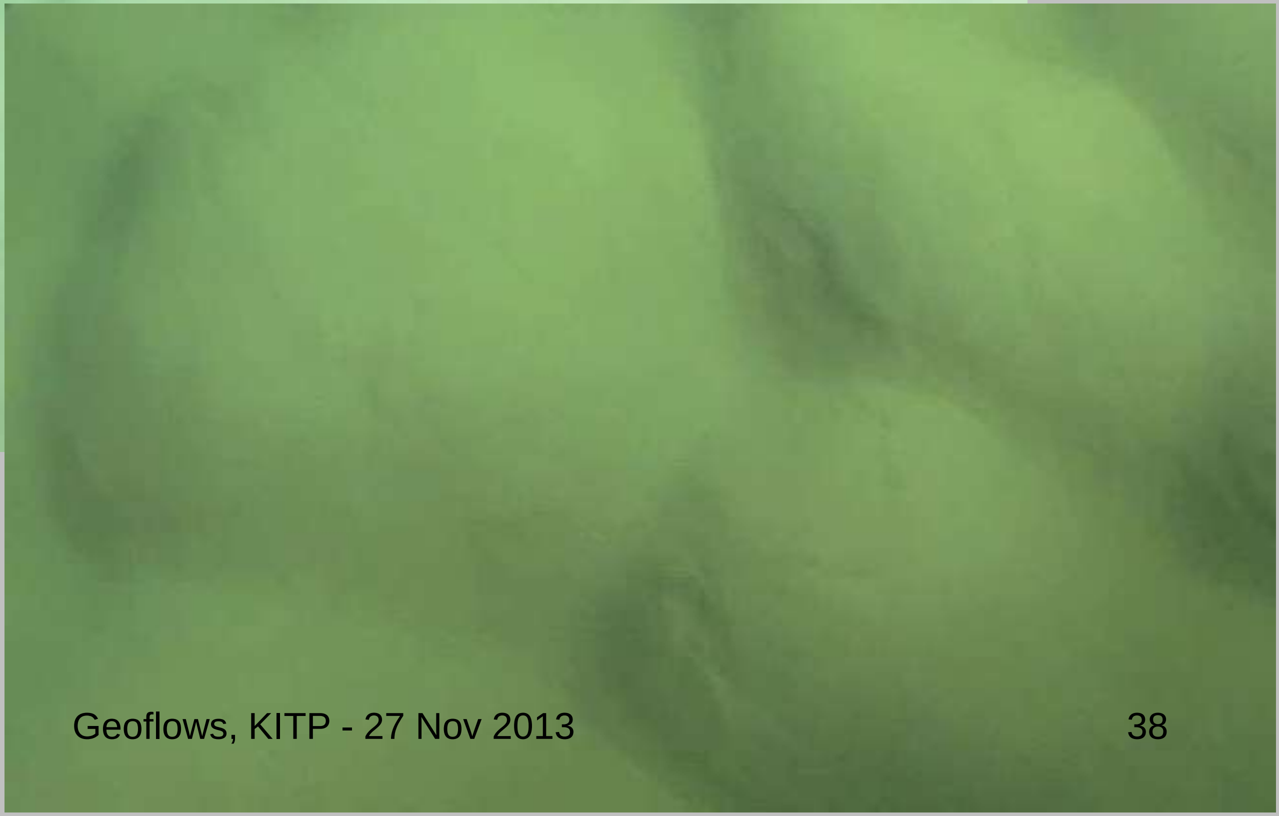
Survey analysis: interactive GIS interface



Processing of stereographic imagery dataset

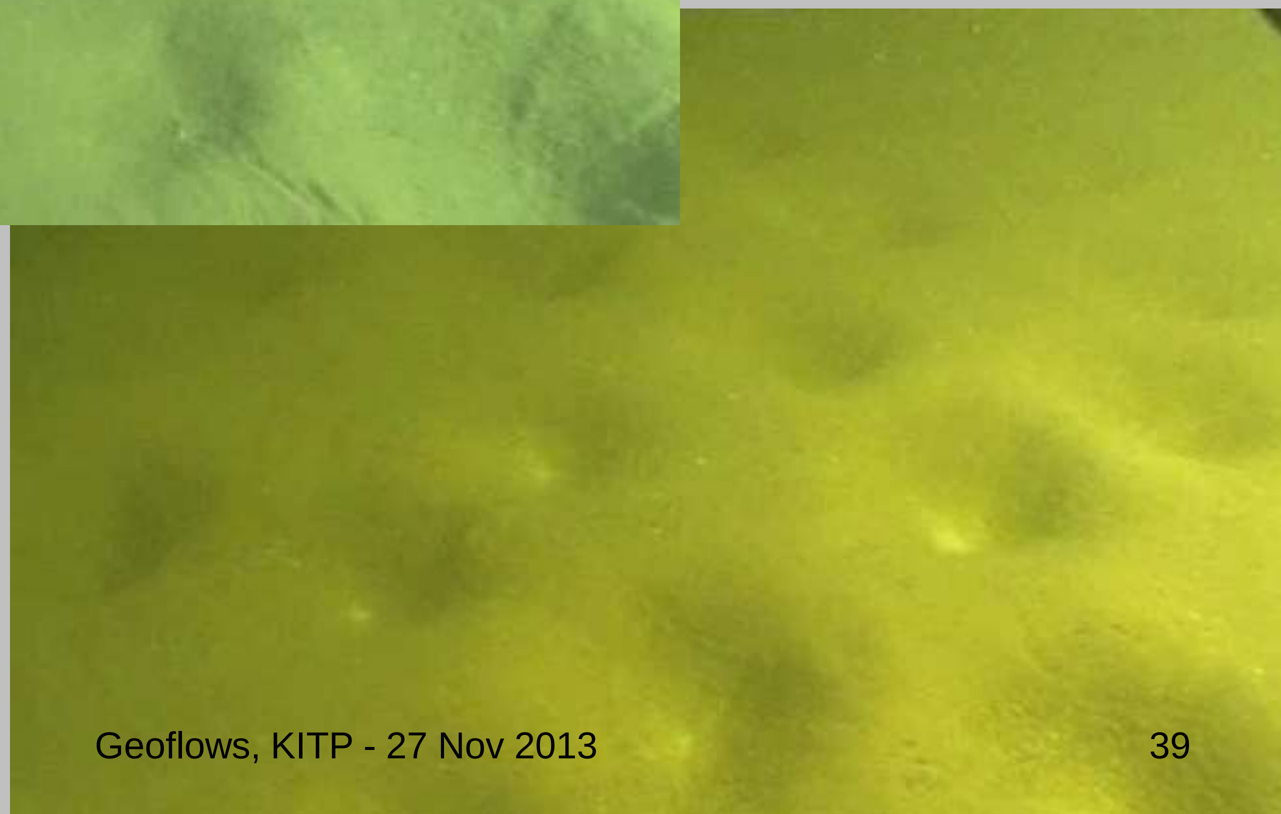


Point Cloud Interpolated Curvature corrected Orthophoto 3D model



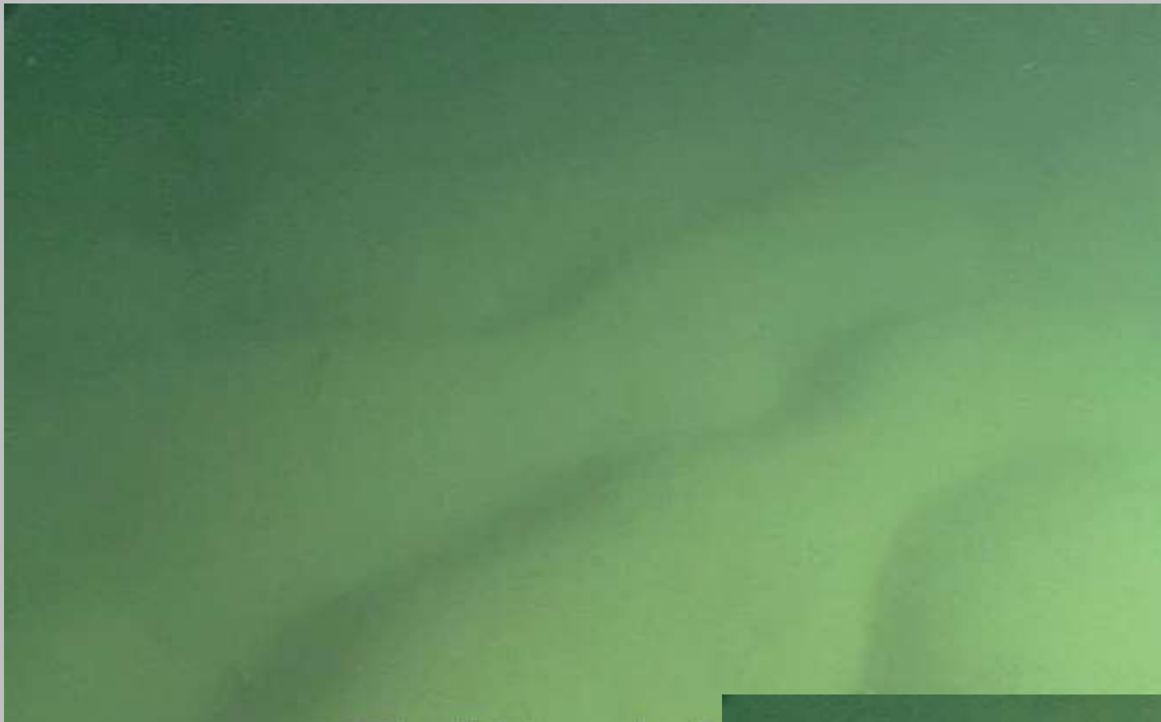
Pillow-hollows

large, well-rounded,
cushion-like structures



Quilted cover

local topographic lows
alternating with highs,
separated by saddles



Sediment waves

Trenches

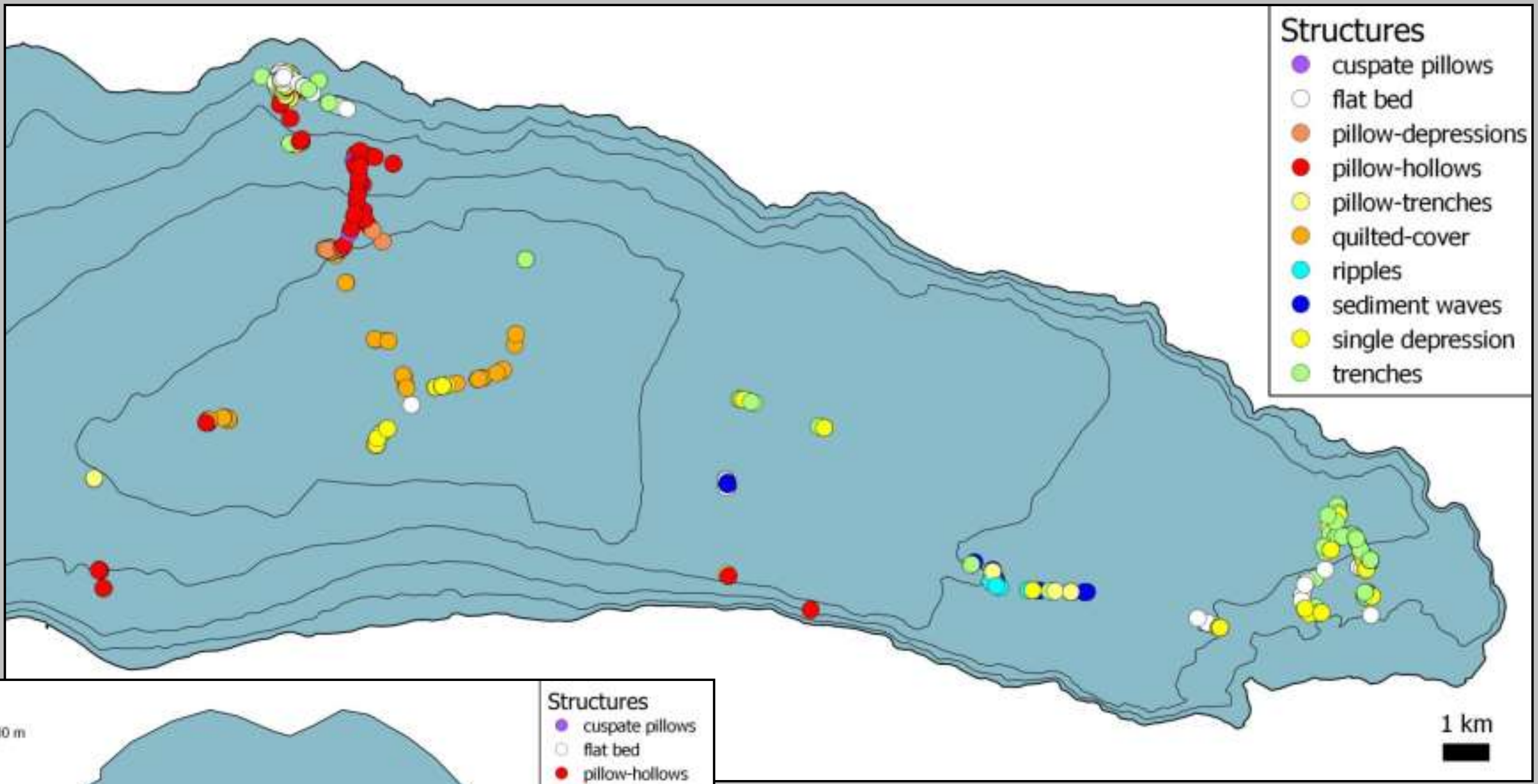
Variations

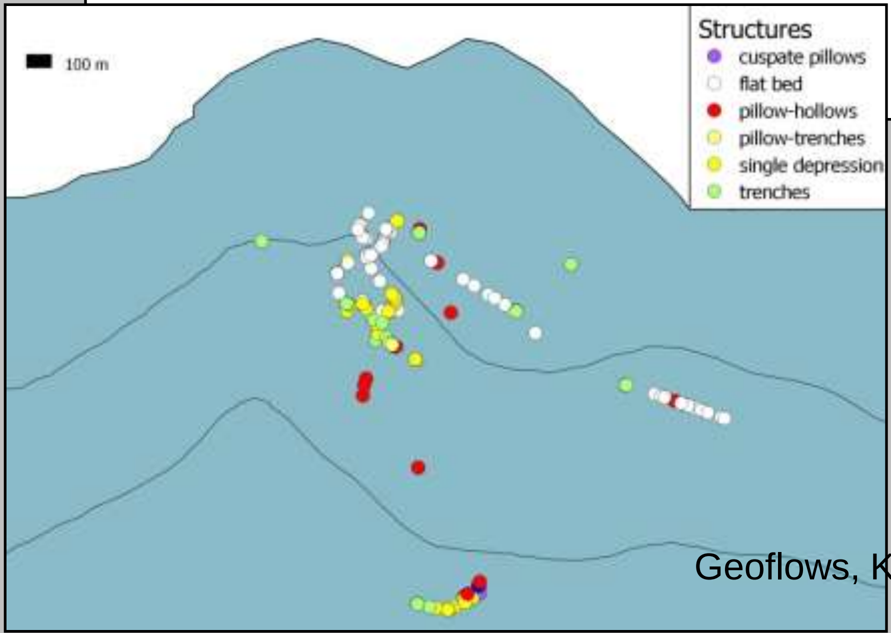
Pillow-trenches

Cuspate pillows

Pillow-depressions

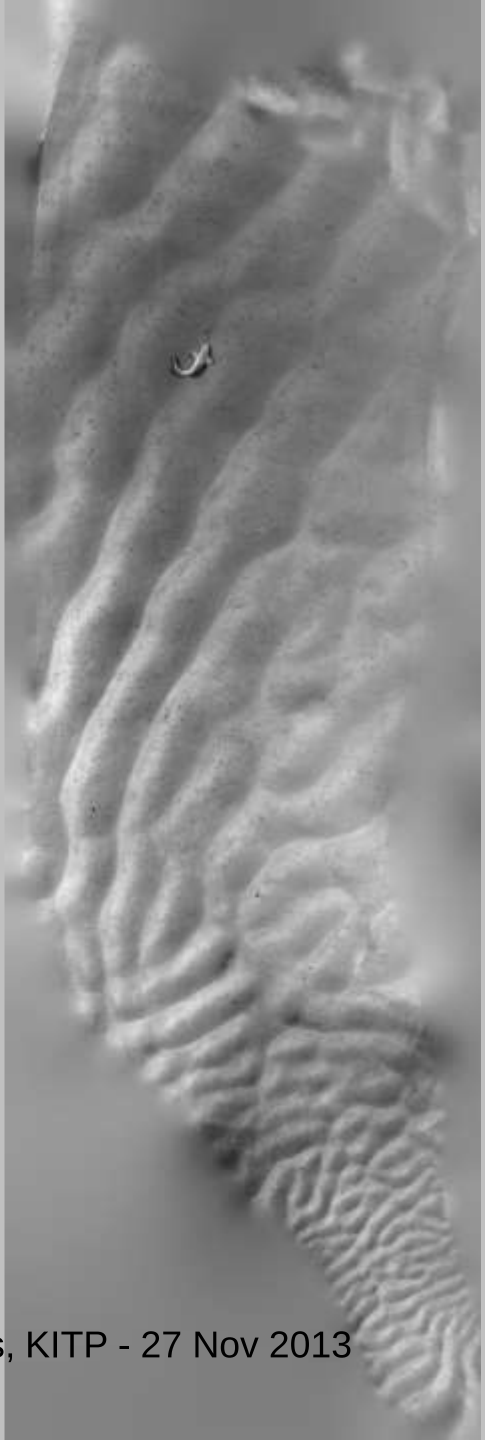
Single depression





Distribution map

⟶ link with forcing factors:
depth, topography, bottom current velocity, …

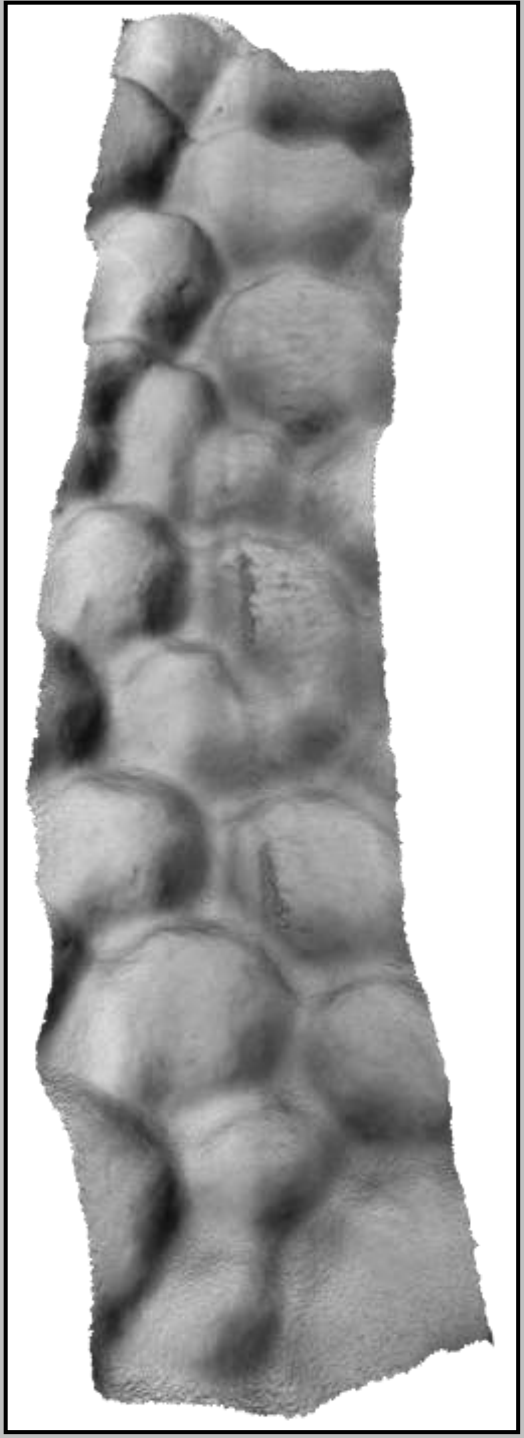


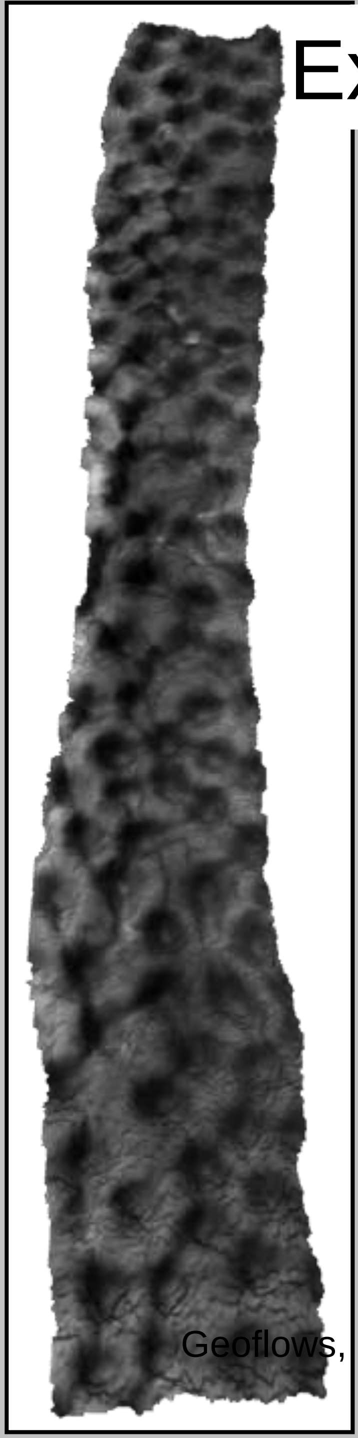
Benefits of 3D models

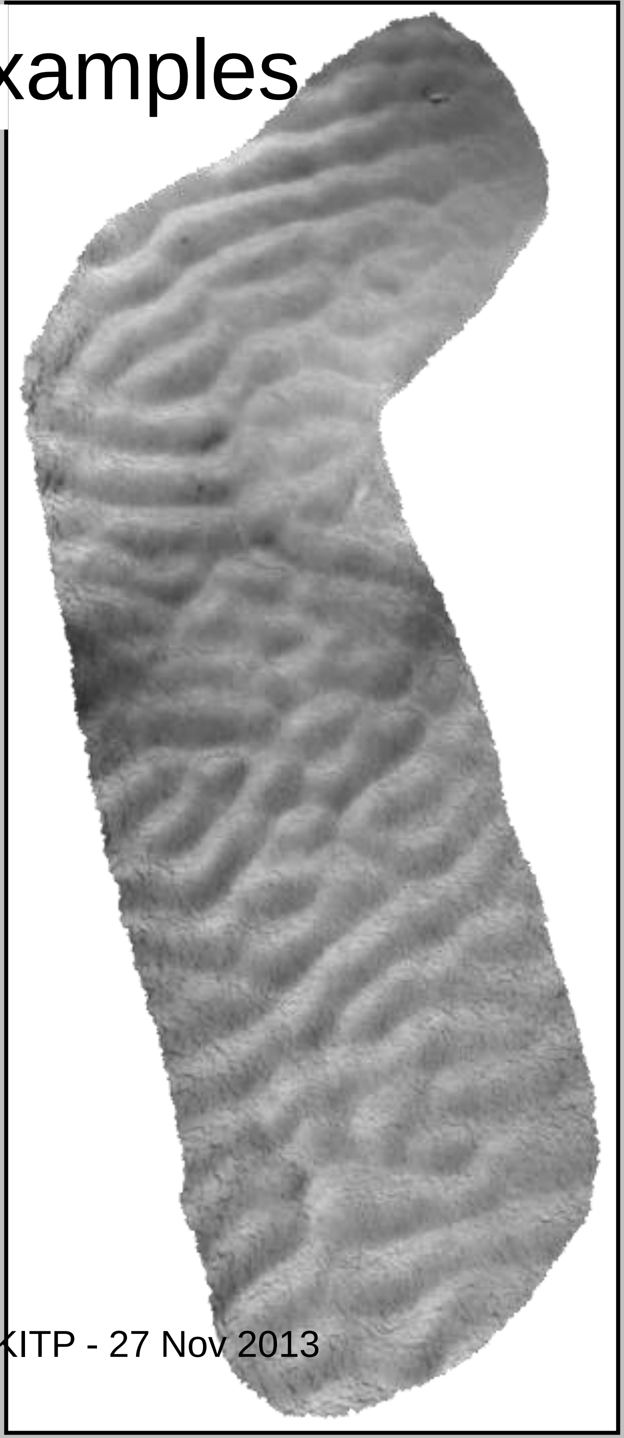
- Morphological characterization without bias from viewing perspective

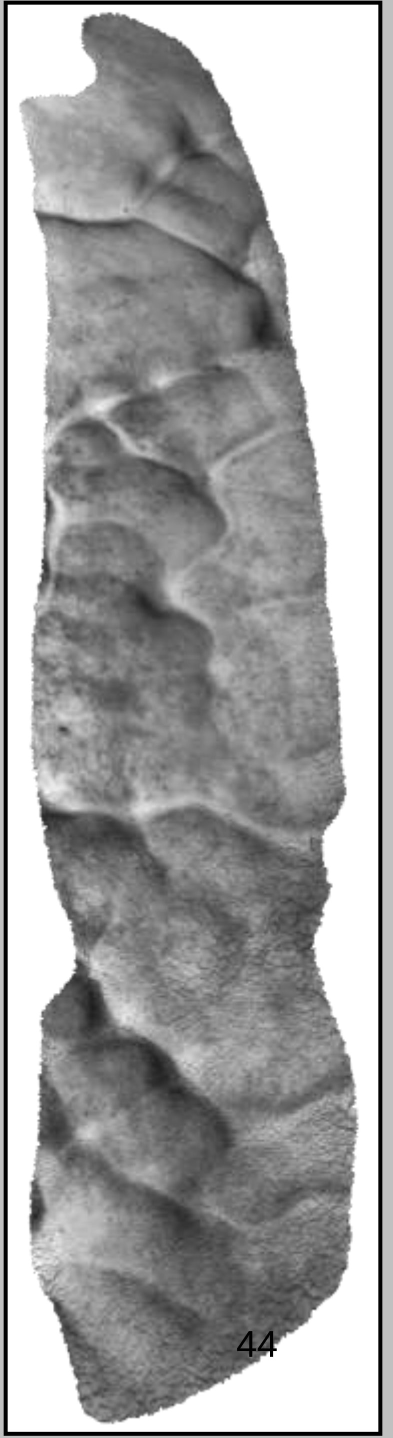
- Extensive 3D models provide a spatial context to examine morphological properties at the level of several consecutive bedforms

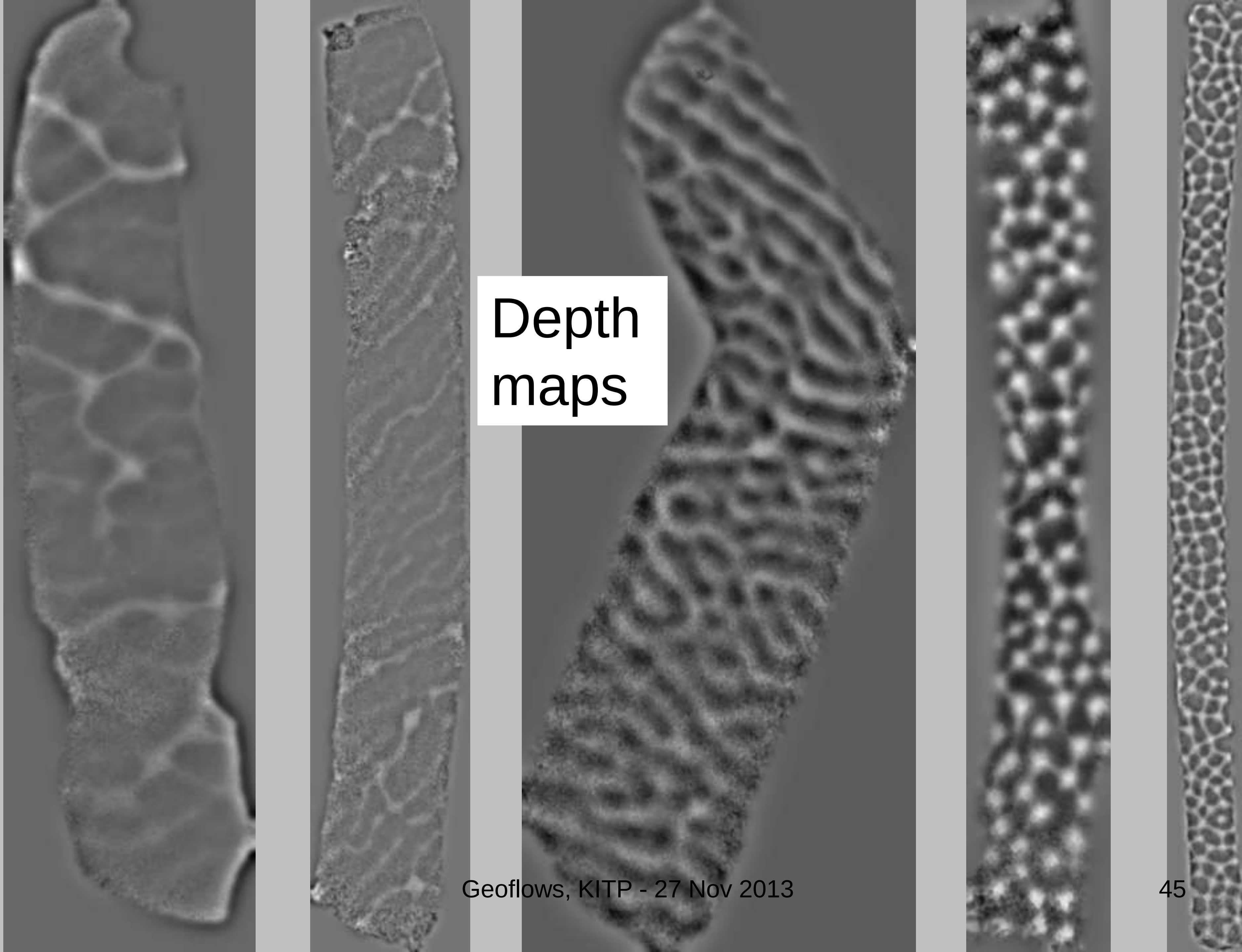
Examples





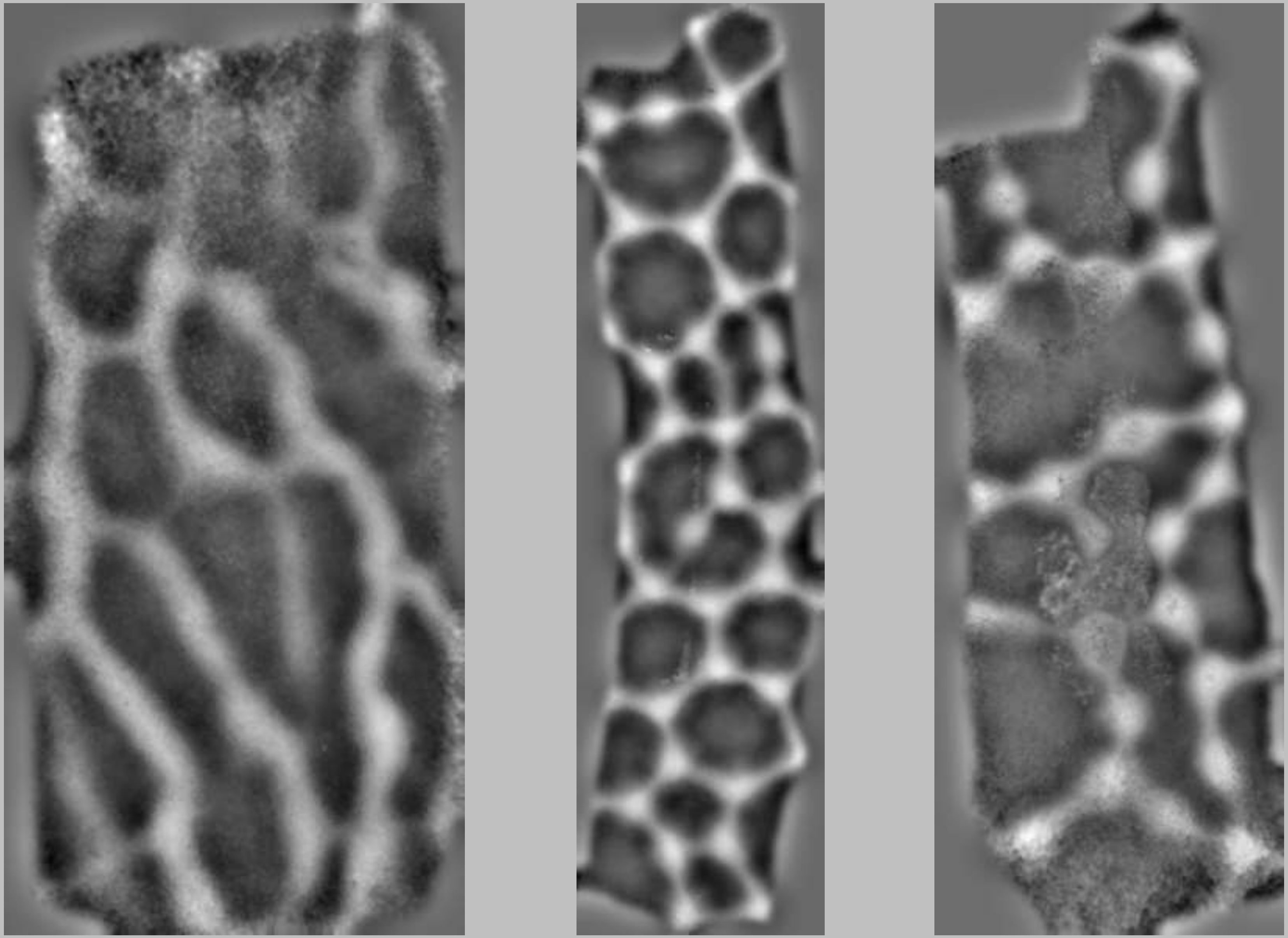




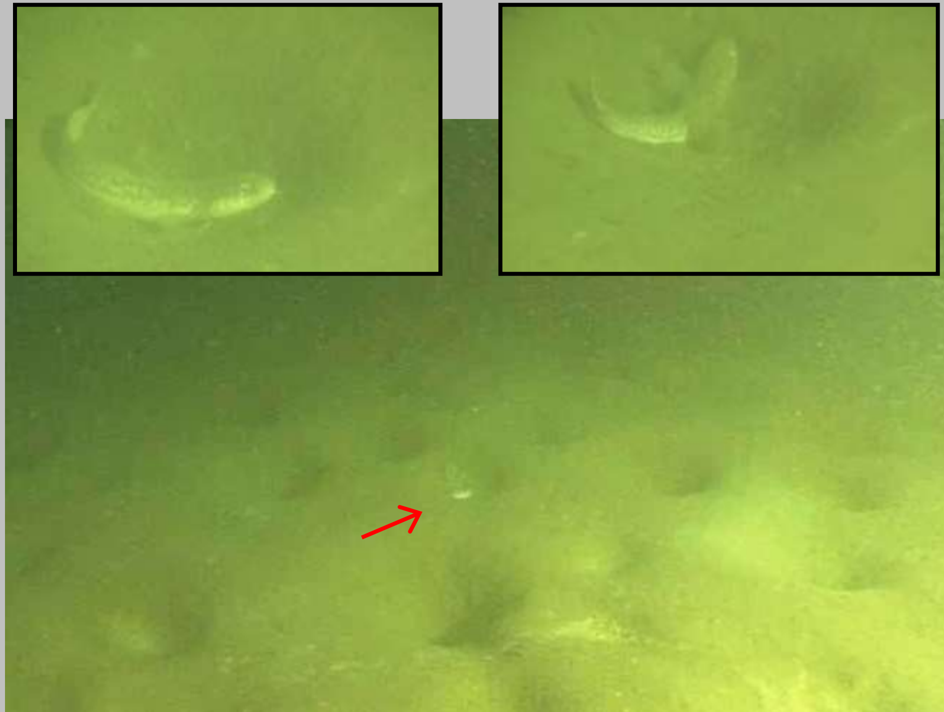


Depth maps

Morphological analysis: level of connectivity



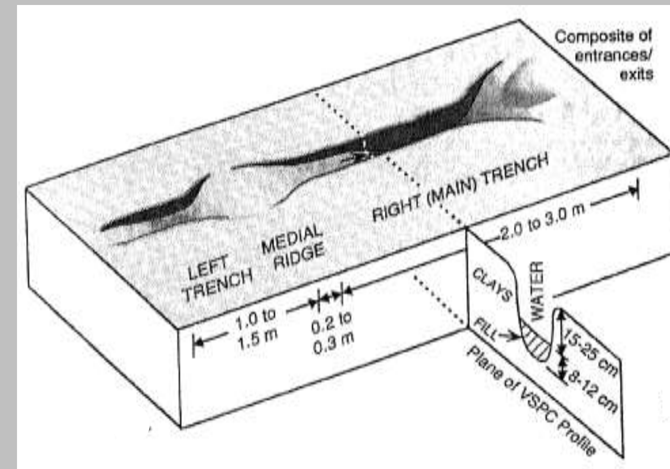
Role of fish



Fish-induced sediment resuspension

… at least maintaining the depressions

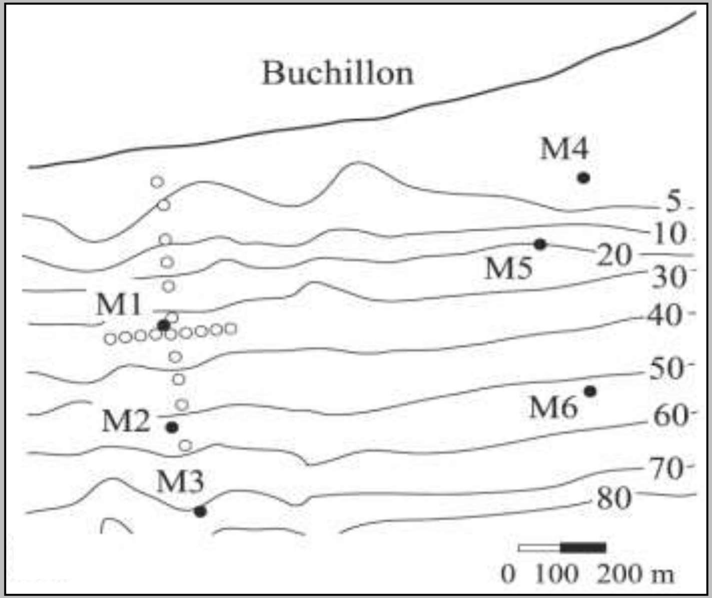
Fish foraging trenches

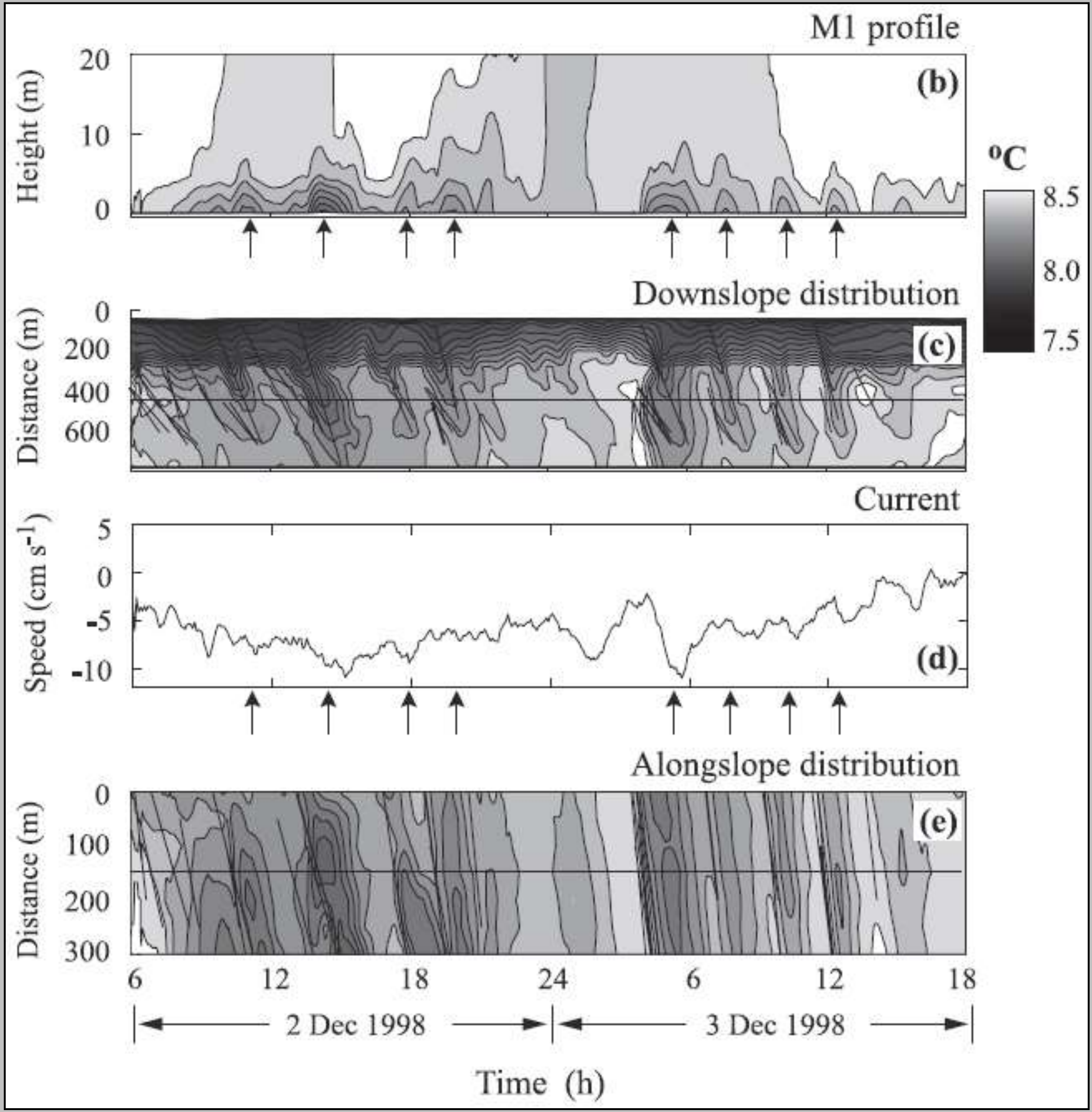


Boyer *et al.* 1989, 1990: Burbot biogenic sedimentary structures in Lake Superior

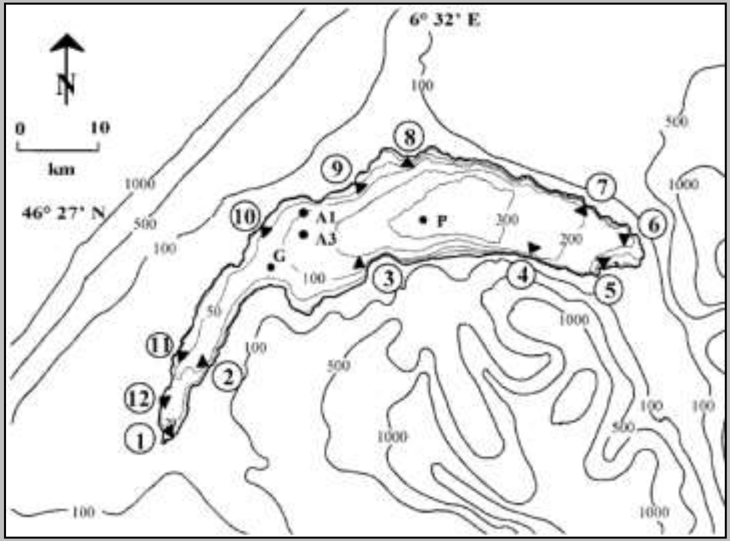
In Lake Geneva

Hydrodynamic forcing ?

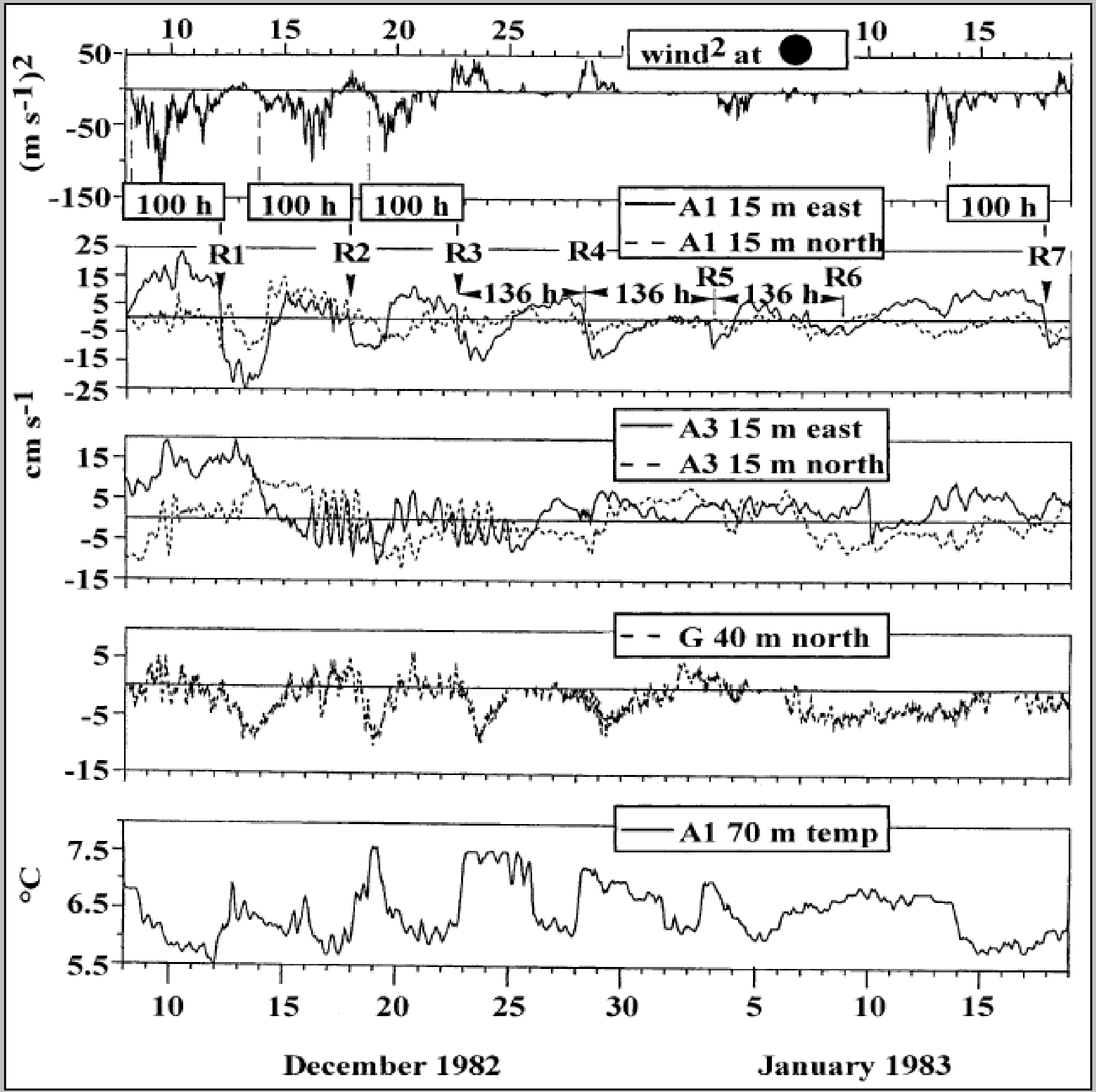




Hydrodynamic processes generating near-bottom currents:
winter cascading flows
(Fer *at al.* 2002)



Hydrodynamic forcing ?



Internal seiche dynamics: shore-hugging Kelvin waves (Lemmin *et al.* 2005)