PS Experimental Study on Bedforms Created by Density Currents*

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Abstract

We report results from more than 350 experimental runs performed with the purpose of investigating bedform patterns created by saline density currents. Combinations among several values of the water discharge, fractional density excess, sediment sizes composing the bed, and bed slopes, allowed for the analysis of the sedimentologic response of the bed to the flow across a full spectrum of the densimetric Froude number (i.e. supercritical, critical, and subcritical flows). Among the major findings we highlight our experimental observation that for such gravity flows, ripples and dunes can form within the supercritical flow regime. This suggests first that bedform regimes are in general much richer than thought before and secondly, that bedforms developed in deep water systems are somewhat different from those developed by subaerial flows (rivers). Therefore, inversion in deep-water environments based on shallow water bedform diagrams and regimes -as currently practiced- is likely to be incorrect. Other important experimental observations include: (1) density current bedform transition from flat beds to different bedform successions follows analogous sequences than subaerial bedforms, when using dimensionless shear stress and sediment size criteria for classification; (2) while ripples were observed to develop through a wide range of supercritical and subcritical flows, large dunes were commonly observed in supercritical flows; (3) upper flat bed regimes where observed to appear at Froude numbers of about 1.6 for fine sediments, and of about 3 for coarser sediments; (4) flat beds or small ripples were the characteristic bedform for flows around and at the critical condition; and (5) an interesting -and somewhat surprising- result included the observation of a different (and perhaps new) kind of bedform that originated as a typical dune- for intermediate and coarser sediment sizes, and typically for values of the Froude number of about 1.2-1.5, evolved with a height comparable to flow thickness, thus interacting with the flow interface, to become a symmetrical, short-wavelength, downstream migrating bedform that resembles a typical antidune. Finally, we investigated first order bedform scaling, and propose an alternative scaling for the case of deep-water supercritical dunes, which appear to follow a similar

scaling law than subaerial subcritical dunes, but with an internal characteristic length (the Richardson layer) rather than the current thickness.

Selected References

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EXPERIMENTAL STUDY ON BEDFORMS CREATED BY DENSITY CURRENTS

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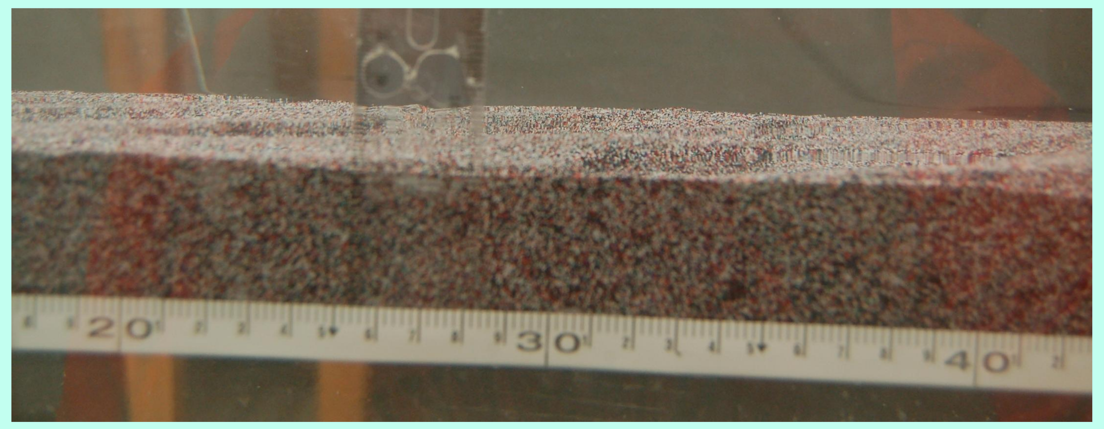
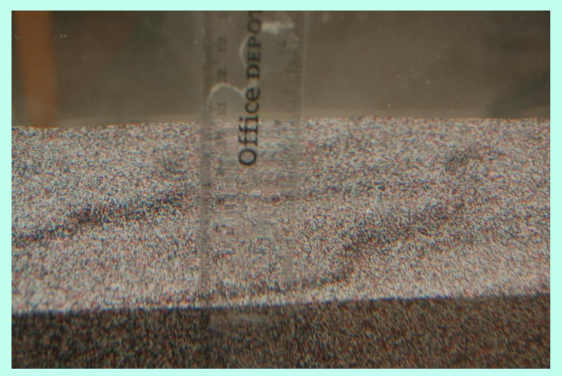
DEEP-WATER BEDFORM SCALING AND REGIMES

RIPPLES





Ripples under supercritical density currents (sed: 200 μ)

Ripples were observed to form for all sediments tested but for 500-600 mm. They appeared in relatively slow moving flows (and low bedload) first as small wavelets, then slowly coalesced and reached final dimensions with no interference to the current interface. Maximum ripple height observed was of about 1 cm, but commonly observed heights ranged from 4-7 mm. They formed in both supercritical and subcritical flows and always migrated downstream.
Ripples were relatively easy to recognized due to their small height and because their wavelengths did scale with sediment size (see plot). During some of the subcritical flow runs, ripples were observed to form beneath currents that were laminar.

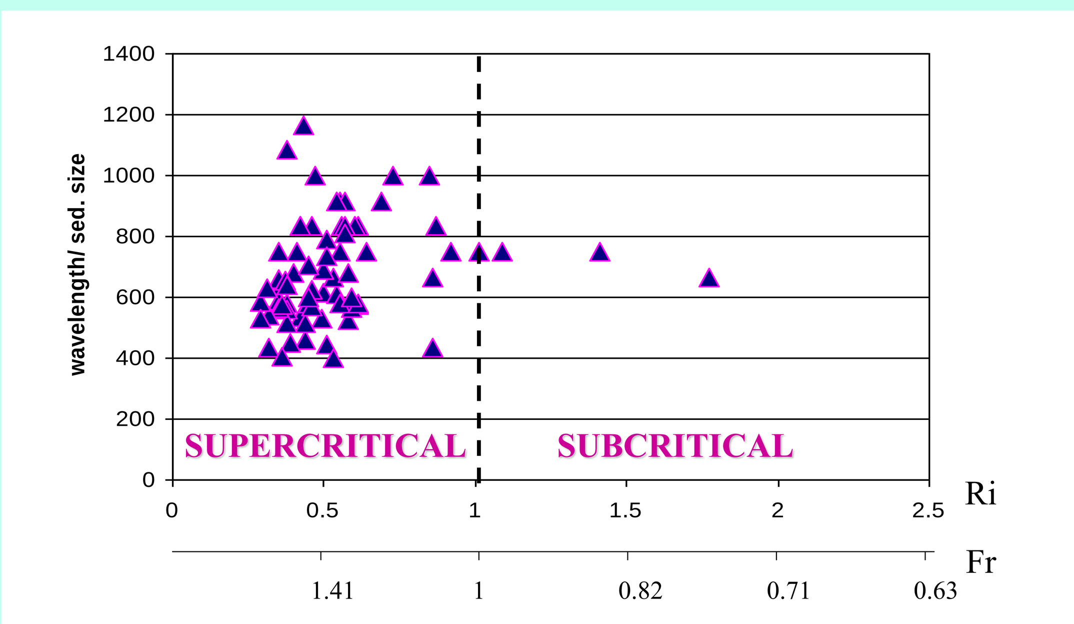


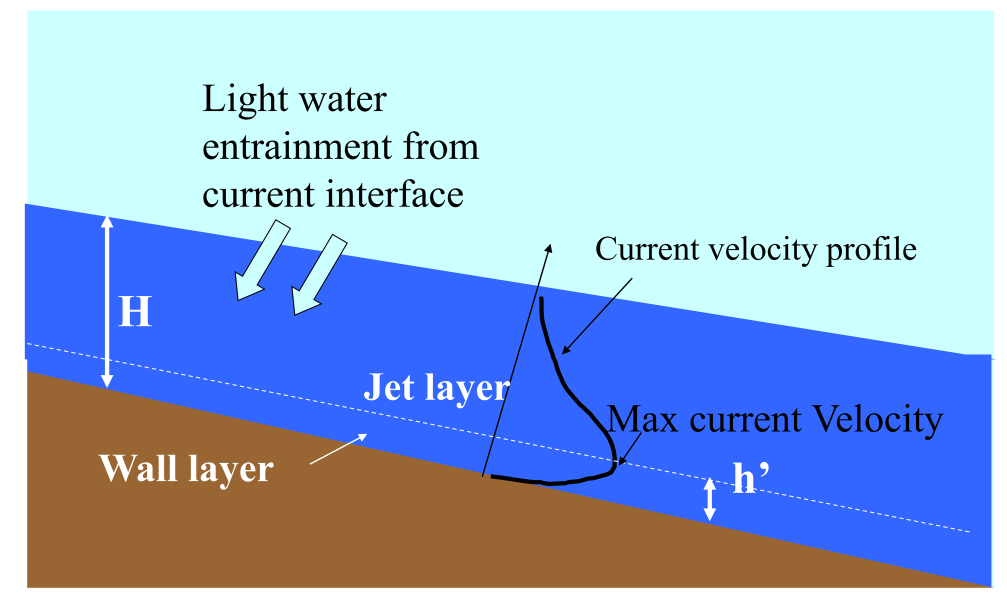
Figure to the left shows a plot of the ripple wavelength to sediment size ratio, as function of the bulk Richardson and densimetric Froude number (bulk Richardson number is defined as the inverse squared of the densimetric Froude number).

This figure suggests a relation analogous to what is known for subaerial ripples (i.e. $\lambda_r \propto D$) (Note also that $R_i > 1$ represent subcritical flows).

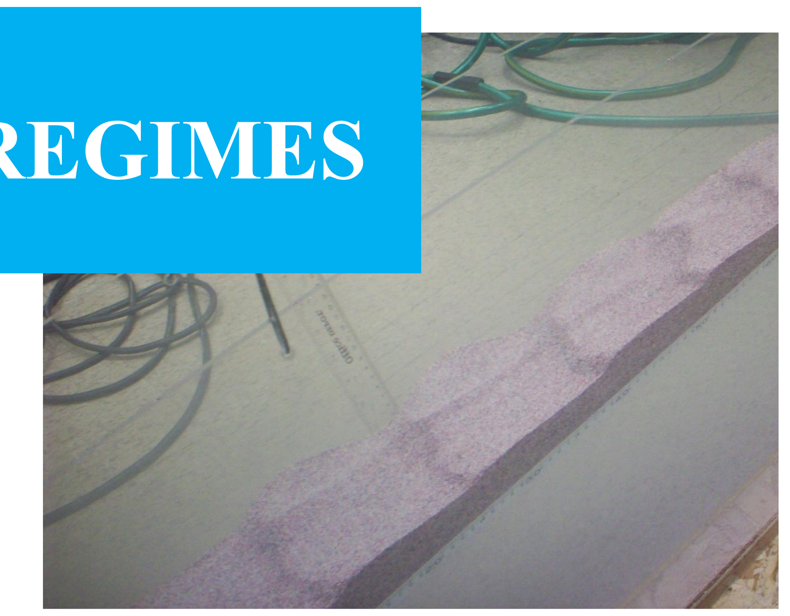
$$\lambda_r \propto D \qquad \frac{\lambda_r}{D} \approx 700 \quad \text{(for this study)}$$

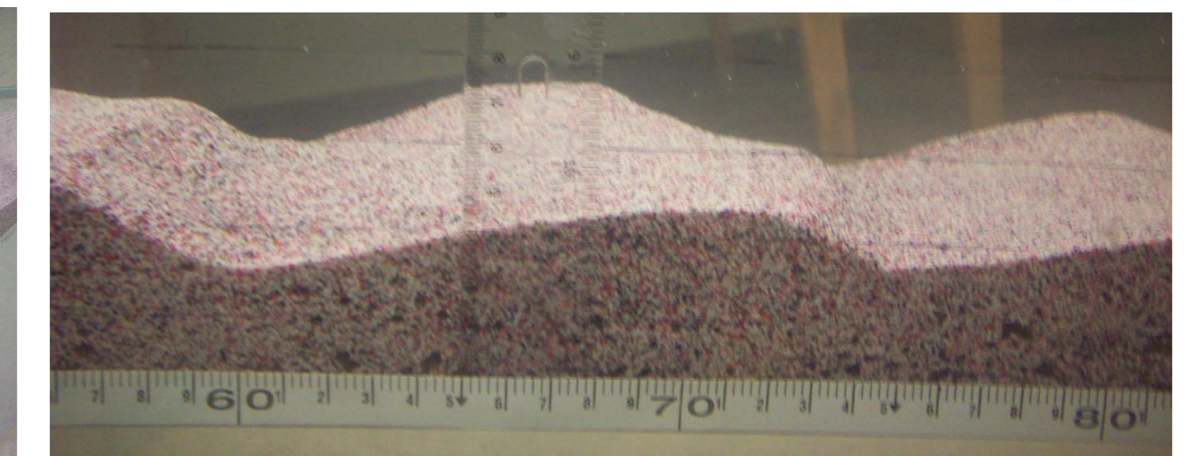
SUPERCRITICAL DUNES

Supercritical Density Current



Sketch of a downslope flowing density underflow





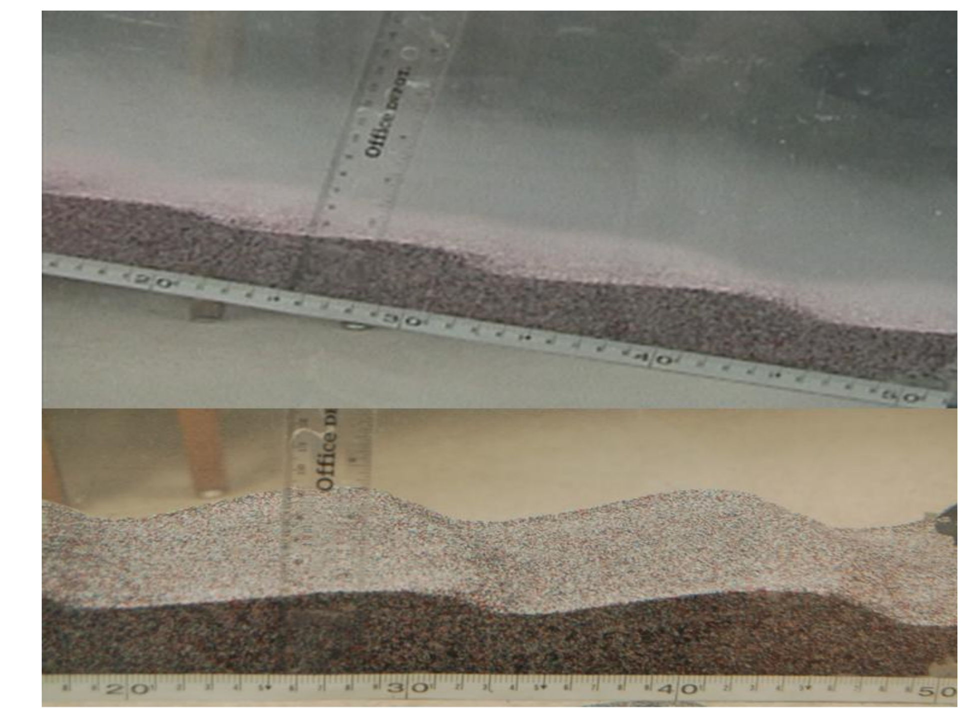
Dunes formed under highly supercritical flows (sed: 500 μ)

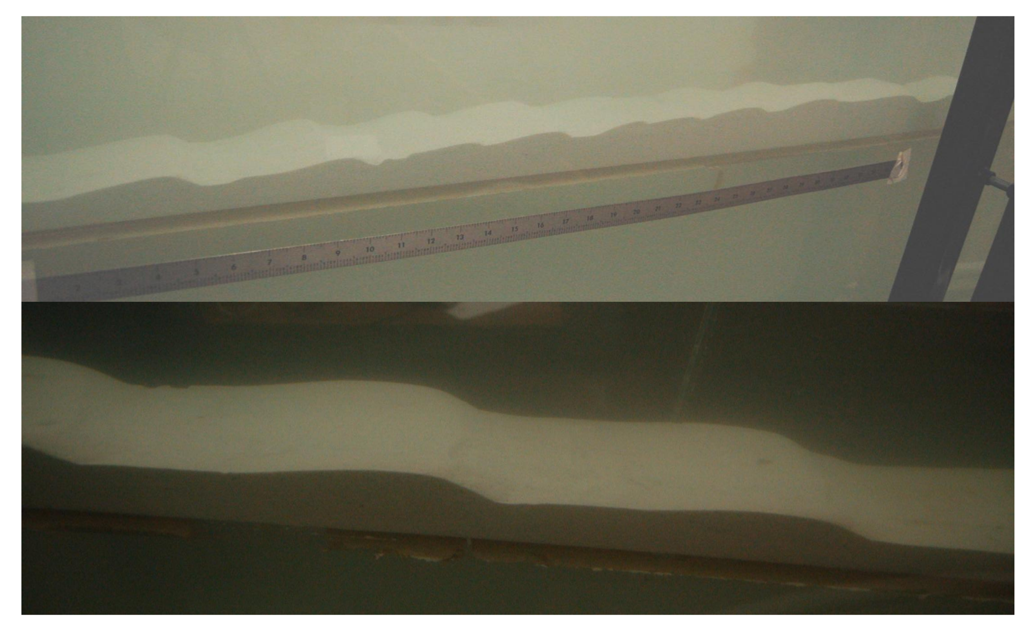
New scaling for deep-water DUNE-like bedforms:

• We assume a density current composed by two layers, the one closer to the bed (wall layer) being relatively denser, with thickness *h'* below the current max velocity (see figure). Flow within this bottom layer is essentially a boundary layer.

• We propose the following scaling: $\lambda = 2\pi h'$

where *h'* is the thickness of the wall layer.

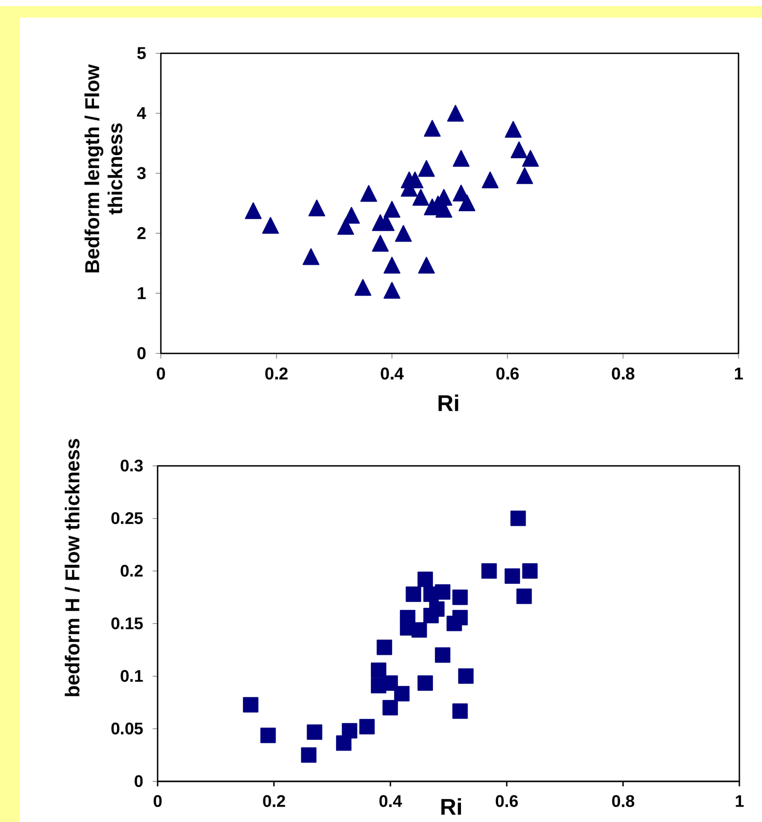




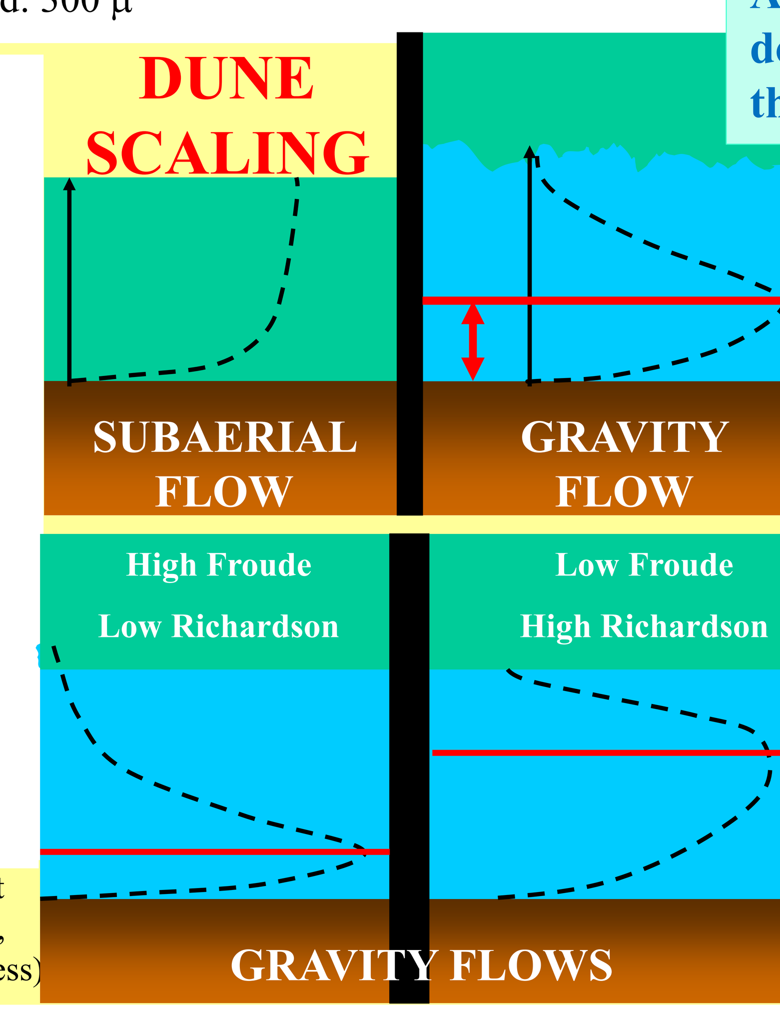
Large dunes formed under supercritical flows (upper picture shows dunes evolving during the experiment, and lower shows final steady configuration). Sed: 300 μ

Bedforms that originated and evolved as dunes were asymmetrical with a slip face (but more rounded than ripples) and with flow separation in their lees, migrated always downstream, and formed under particularly high Froude numbers. While the distinction between dunes and ripples was occasionally difficult, dunes were in general easier to identify since their wavelength was set immediately as they appeared on the sediment beds, and they developed under flows with larger bedload rates. They evolved at faster rates than ripples, and they were observed to form for the intermediate and coarser sediment sizes. Dune wavelength was observed to be sensitive not only to current thickness, but also to the Richardson number. Observed dune heights ranged around 1-2 cm. Preliminary visualizations aided by coloring currents, and analyses of filmed runs indicated that they formed independently of any interface deformation. As they evolved, it was also observed that there was little to no interactions between dunes and the current interface, even at their final evolved stages.

Although the argument could be made that these particular bedforms might be downstream-migrating antidunes, we emphasize once more the relevant aspect of how the bedforms originated and evolved.



Analysis of their heights and wavelengths suggests that dunes are sensitive to a characteristic flow length scale, but different than flow thickness (i.e. wall layer thickness)



Assuming that supercritical dunes are the result of near-bed processes analogous to those present in subaerial flows, we propose that a more appropriate length scale is the thickness of the layer near the bed where the velocity distribution is analogous to that of a boundary layer flow, i.e. where the velocity gradient is positive (wall layer, Richardson layer). Since the thickness of this layer is in turn a function of the Richardson number, then dune height and wavelength should be also a function of the Richardson number. Garcia (1989) reported experimental results on density current velocity and density distributions that suggest that for supercritical flows, the thickness of the boundary layer increases as critical conditions are approached. This is consistent with our observations that for highly supercritical flows, the flow in the wall layer is thinner and pushed down by a relatively thicker mixing (jet) layer above the velocity maximum, therefore limiting growth of dune height.

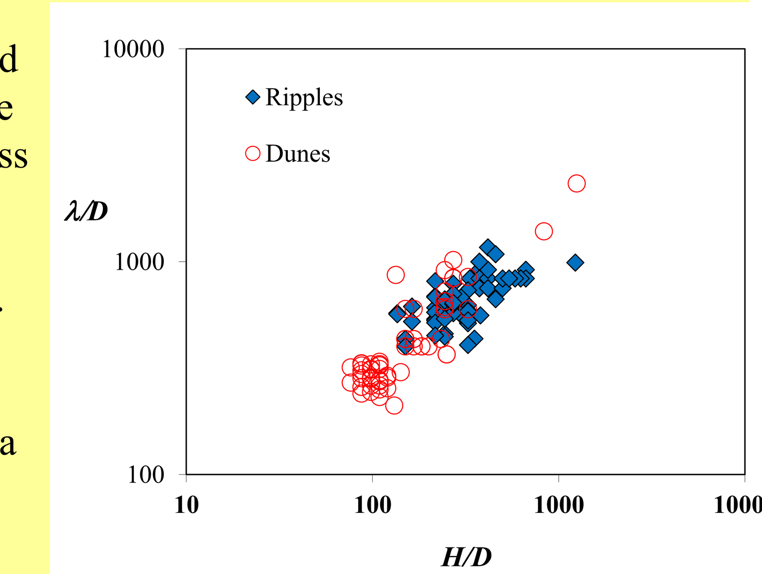


Figure above includes ripples and dunes, and shows the insensitivity of ripples to current thickness and the sensitivity of dunes to a characteristic current length scale (thickness). (see for example Yalin, 1977; Bridge, 2003).

DUNES UNDER SUPERCRITICAL CURRENTS?

If the scaling $\lambda = 2\pi H$ is used (here λ is bedform wavelength and H is density flow thickness) for the case of dunes, for example, then using typical values of density current thicknesses in the field (tens to hundreds meters) would produce dunes up to…km long! …there are observations of both asymmetrical and symmetrical deep-water bedforms 1-5 m long.

A simple exercise using shallow-water bedform regime and scaling in deep-water bedforms might be instructive to explain some inconsistencies:

$$F_{rdc} = \frac{U}{\sqrt{\frac{\Delta\rho}{\rho} gH}}$$

The densimetric Froude number used in the case of density underflows is given to the left (where U is mean current velocity, H is current thickness, and g $\Delta\rho/\rho$ is the 'reduced' gravity)

Assuming 'full' equivalence between shallow and deep water bedform regimes, for approximately equal flow velocities between a subaerial river with flow depth h and a density current of thickness H, Froude similarity gives:

$$H = \frac{h}{\Delta\rho/\rho}$$

Using $h = 1$ m for a river, and a (large) excess density fraction $\Delta\rho/\rho = 0.01$, gives $H = 100$ m. Then considering the usual dune scaling relation leaves us with a value of dune wavelength equal to …1 km!

SOME OBSERVATIONS:

• During phase of development, some bedforms under supercritical gravity flows appear to develop independently and without any interaction with current interface (thus, no antidunes…).

•They appear for moderate (to high) values of the shear stress (transport), with a clear and defined wavelength, they then coalesce soon, and their wavelength evolve to a steady length (larger than that observed at early stages of formation).

• Their final wavelength tend to slightly increase downstream, indicating some relation to current thickness (in supercritical currents, current thickness increases downflow due to water entrainment) (wavelengths observed range from about 10 cm to 25 cm)

•They develop in fine-to-medium, medium, and coarser sediments.

• Their height remains small compared to flow thickness, and it appears that its growth is limited and controlled by strength of flow in wall layer, along with thickness of jet layer above.

EXPERIMENTAL STUDY ON BEDFORMS CREATED BY DENSITY CURRENTS

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MOTIVATION OF THE STUDY

- Field observations suggest that small-scale bedforms such as dunes or ripples (wavelengths ranging from 10 to few tens of centimeters, to 1 to few meters) are not uncommon in deep-water environment deposits (i.e. density or turbidity current origin) (see Figures 1 and 2)
- Knowing the relations between a given type of bedform and its associated flow allows us to solve inverse problems, such as (1) infer paleoflow conditions, (2) infer the environment (hydrodynamic and morphodynamic conditions) under which bedforms were formed, (3) interpretation of sequences of bedform deposits, (4) infer sediment sources and distance to sources. All these from observations of geometry and sediment type in deposits.
- Associated to inverse problem solution is the question of whether or not a given bedform geometry is unique of a give bedform type (i.e. ripples, or dunes, or antidunes)

Figure 1. Bedform bedding, Tanqua Karoo Form. (S. Africa)

Figure 2. Longer (2 m) wavelength bedforms. Tanqua Karoo Form. (South Africa)

- Experimental work (Fedele, current work); Hoyal, at EMURC) suggest that mechanics of bedforms in deep-water environments is different from shallow-water (subaerial) flows, with possibly a different development and existence regimes.
- Thus, inversion problems for deep-water based on shallow-water bedform regimes –as currently practiced) is likely to be incorrect.

OUR GOAL

Characterize the mechanics, geometry, scaling, and regime existence (phase diagram) of small-scale deep-water bedforms (e.g. ripples, dunes, antidunes) created by density underflows such as density or turbidity currents

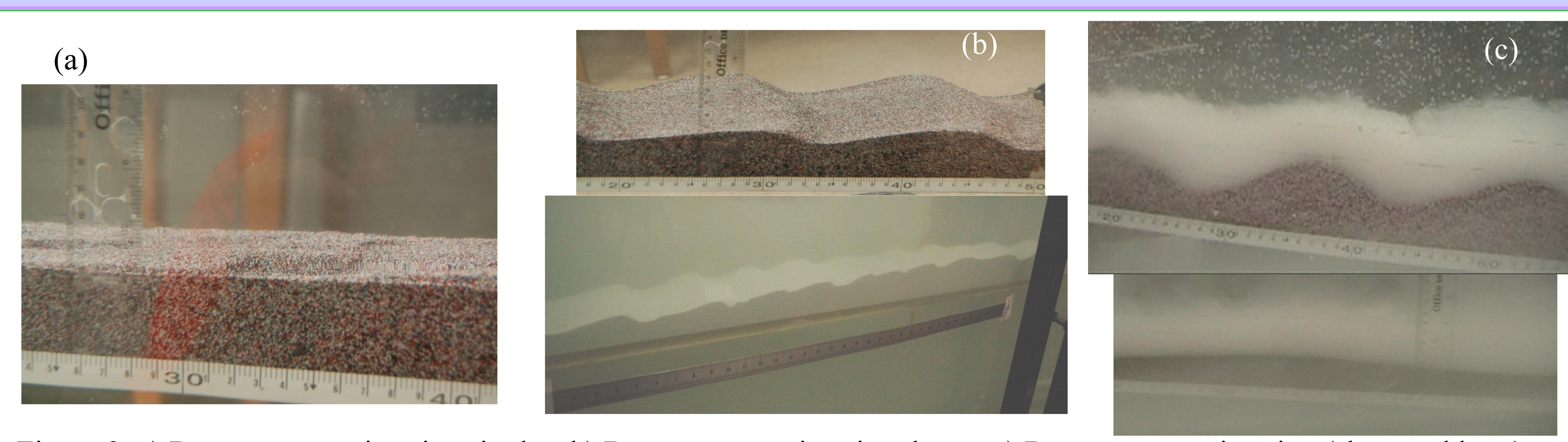


Figure 3. a) Downstream-migrating ripples; b) Downstream-migrating dunes; c) Downstream-migrating (short and long) antidunes. All these were created under supercritical (desimetric Fr > 1) saline density currents

BEDFORM BACKGROUND

SHALLOW-WATER (Subaerial streams)

RIPPLES, DUNES } SUBCRITICAL FLOWS (Fr < 1)
ANTIDUNES → SUPERCRITICAL FLOWS (Fr = OR > 1)

- RIPPLES: usually develop in fine sediments, with low flow velocities, and low transport. Downstream-migrating, asymmetrical with wavelength scaling to grain size and insensitive to any flow-related length scale. Can coexist with larger dunes (superimposed). They are asymmetric and form always in subcritical flows. Can develop in closed conduits (no free surface)
- DUNES: develop in medium or coarser sediments, larger and gentler than ripples. Their wavelengths are highly sensitive to flow depth in turbulent flows, with $\lambda = 2\pi h$ (λ is bedform wavelength and h is flow depth) (Kennedy, 1967). Dune amplitude is always a small fraction of flow depth. They are asymmetric and characteristic of subcritical flows. Can develop in closed conduits (no free surface)

ANTIDUNES: down or upstream migrating, can be about same or larger than dunes. Characteristic of critical and supercritical flows, they are associated with deformation of the free surface. Their amplitude is larger than dunes, in some cases of the order of the flow depth. Can be symmetrical or become asymmetrical for higher Fr numbers.

DEEP-WATER (Density underflows)

RIPPLES, DUNES } REGIME NOT KNOWN
ANTIDUNES → SUPERCRITICAL DENSITY OR TC

- RIPPLES AND DUNES: phase regime is not known. Experimental evidence (this work; Fedele, PhD Thesis; Hoyal, EMURC) shows that downstream-migrating ripples or dunes can occur in supercritical density or turbidity currents, or superimposed to long-wavelength antidunes (also in supercritical flows)
- ANTIDUNES: down or upstream migrating. We recognize two types:
  1) Long-wavelength antidunes, known commonly as 'sediment waves' with wavelengths of the order of 1 to few kms, observed in continental rise and levees of submarine canyons (literature reveals no agreement in relation to terminology and basic processes in charge of their formation; Parker cyclic steps?)
  2) Short-wavelength (cm to m) antidunes (see Figs 1 and 2 above). Reported in this work. Fig 3 (c) above.

In all cases (ripples, dunes, antidunes), practice has been to extrapolate what we know about shallow-water (subaerial) bedforms to the case of deep-water (density or turbidity current) bedforms. This work suggests that bedform regime for gravity flows might be richer and somewhat different than subaerial bedform regime.

Deep-water (gravity flow) ripples on dunes. Laingsburg (South Africa)

Laingsburg, South Africa. Deep-water (gravity flow) ripples

Tanqua Form. – South Africa Short-antidune internal structure

OUR WORKING HYPOTHESIS

RIPPLES

- Downstream-migrating ripples form in shallow-water for low values of the shear stress (transport) and fine sediments. Ripple scaling is insensitive to flow depth (current thickness) and responds only to sediment size. We keep this premises to define RIPPLES for deep-water systems

DUNES

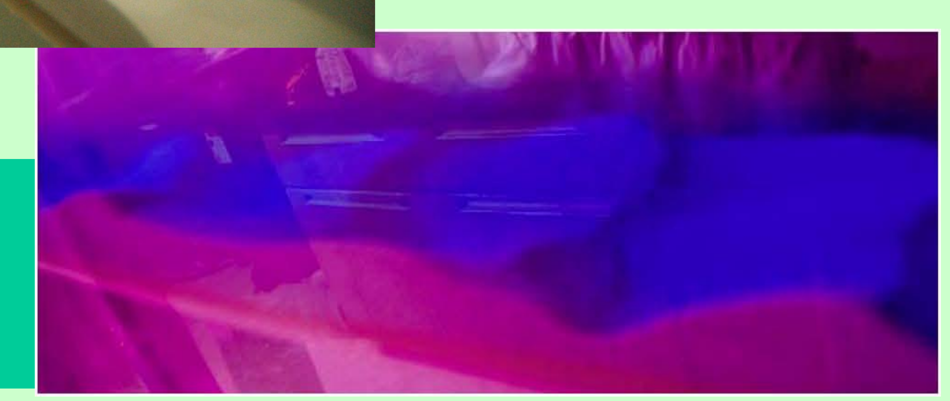
- In shallow water systems, dunes (subcritical flows only) and antidunes (supercritical flows) might be of similar scale: dune wavelength $\lambda = 2\pi h$; antidune wavelength λ = 13-20 h (dunes have never been observed to form under supercritical flow; antidunes obliterate dunes in supercritical conditions).
- Dunes form for higher values of the shear stress and transport. Instability mechanisms in charge of their formation are not associated to free surface (rivers) (i.e. current interface for gravity flows). We keep these premises to define DUNES under gravity flows.
- Experimental evidence suggest that RIPPLES or DUNES can coexists with long antidunes

ANTIDUNES

- In deep-water systems antidunes appear to be of much longer wavelength (order of km) and scale with current thickness H (long sediment waves) . These are not considered in detail in this work.
- Field and laboratory evidence indicates that smaller, symmetrical bedforms (wavelength of the order of tens of cm or m) resembling symmetrical antidunes are also common (figures 1 and 2). We consider these short-wavelength symmetrical antidunes in this work.
- Regardless their wavelength, we define antidunes as those bedforms that are the result of instability mechanisms in current interface in supercritical gravity flows (just like antidunes in subaerial flows).

EXPERIMENTAL METHODS

Experimental runs were performed in a 6 m long, 0.15 m wide plexiglass flume where initially flat sediment beds were placed before each run. The flume was submerged in a larger, deep tank filled with tap water, with a free surface control. Density currents were created by mixing fine-flake salt and water with same temperature as in the larger tank.
Incoming water discharge was accurately measured using an acrylic rotameter with float. Detailed velocity profiles were measured at selected verticals using ADV. Density profiles where also measured in same verticals where flow velocity was measured, sampling every 5 mm using a system of siphons and an optical refractometer. Density profiles were also measure at flume entrance and exit, before the density current free fall.



Experimental values

Water discharge [liters/s]	Sediment size [mm]	Flume slope	Current Specific Gravity
0.16	100-120	0.017 (1°)	min 1.001
0.28	180-200	0.043 (2.5°)	max 1.057
0.38	300	0.087 (5°)	
0.76	500-600	0.176 (10°)	

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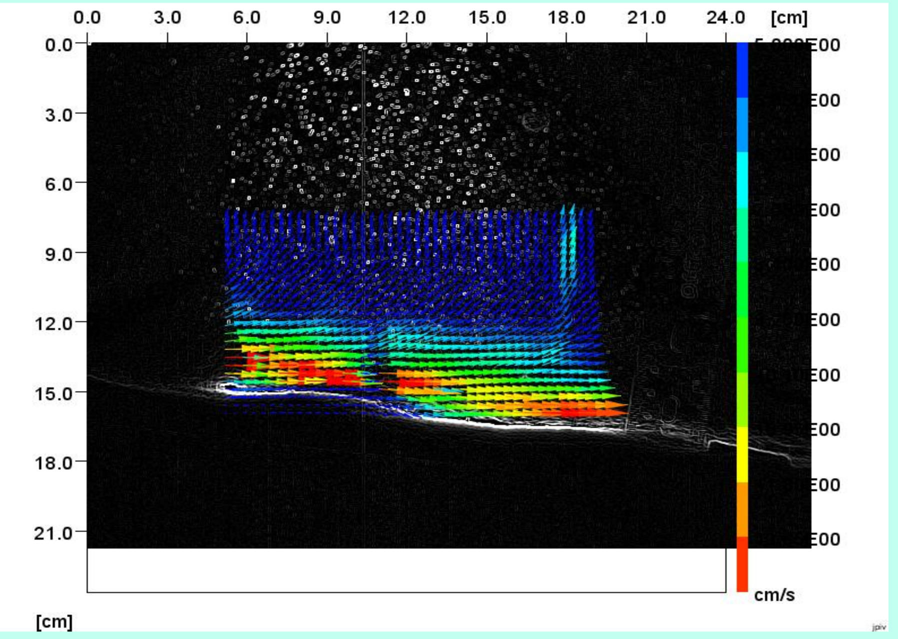
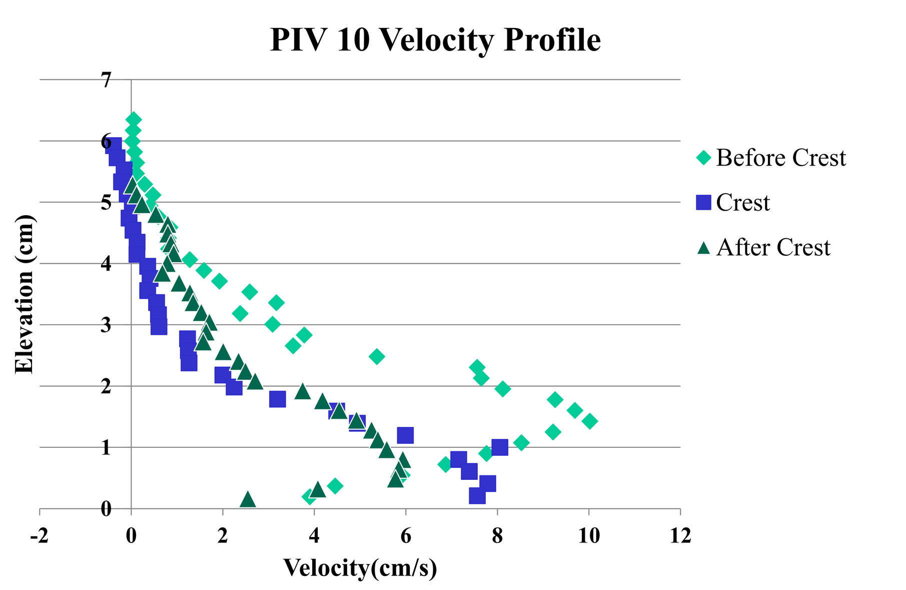
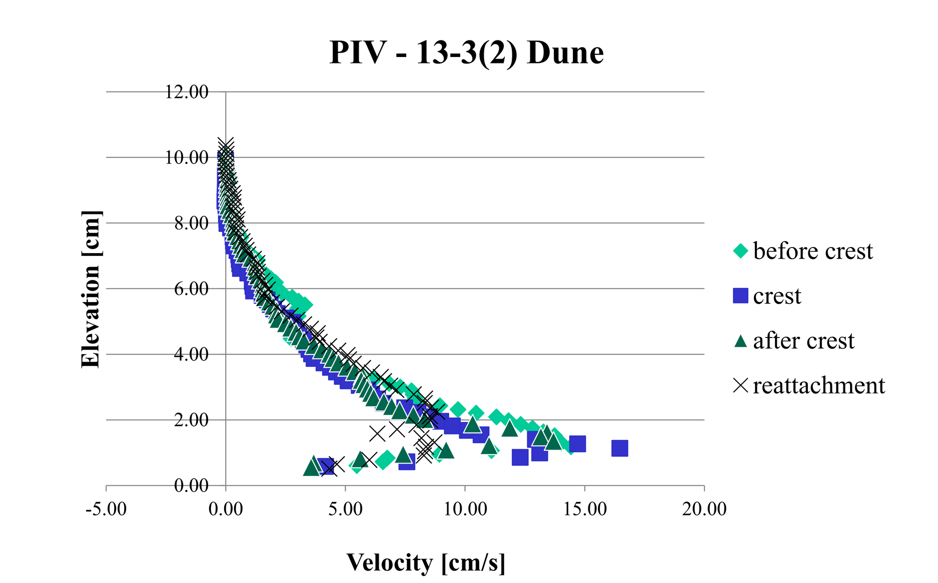
SUPERCRITICAL DUNES SCALING: PIV ANALYSIS



- PIV was used to obtain detailed velocity vector fields over entire wavelengths of supercritical dunes, to further investigate dune wavelength and height scaling.
- Velocity distributions of the streamwise component were extracted from the PIV vector fields at high density over an entire wavelength, and spatially averaged for a given run (with a given set of parameters)
- A given set of parameters were repeated several time, and PIV was used in each, in order to obtain ensemble averages of the spatially averaged profiles over a particular dune
- The ensemble of the spatially averaged profile was then used to obtain thickness of the wall layer, and relate with dune wavelength.

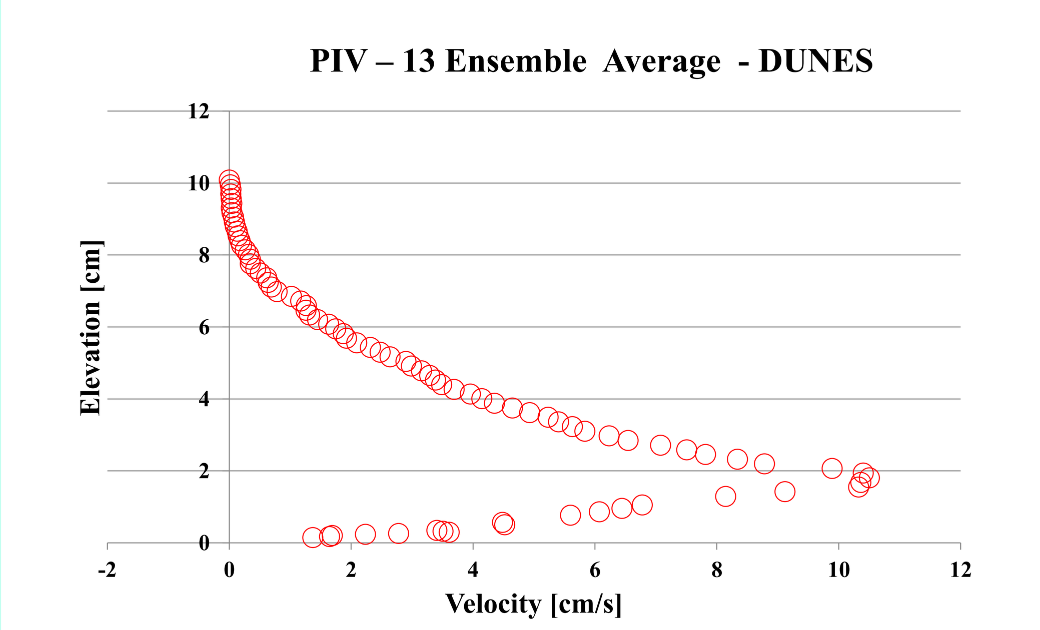


Ri = 0.35 (Fr = 1.7); Dune wavelength = 10 cm



Ri = 0.6 (Fr = 1.3)
Dune wavelength = 14.1 cm ; Dune height : 0.85 cm

Figures on the left show examples of local velocity distributions obtained from PIV measurements over dunes. These profiles were used to obtain spatially-averaged profiles for each set of hydraulic-sedim parameters, and a characteristic (average) bedform wavelength.



Ensemble spatially-averaged velocity distribution – The height of the wall layer used to dune scaling was extracted from these, for each set of flow parameters and average dune wavelength. Ensemble averages were computed from spatially-averaged (over a bedform wavelength) profiles from each particular set of parameters.

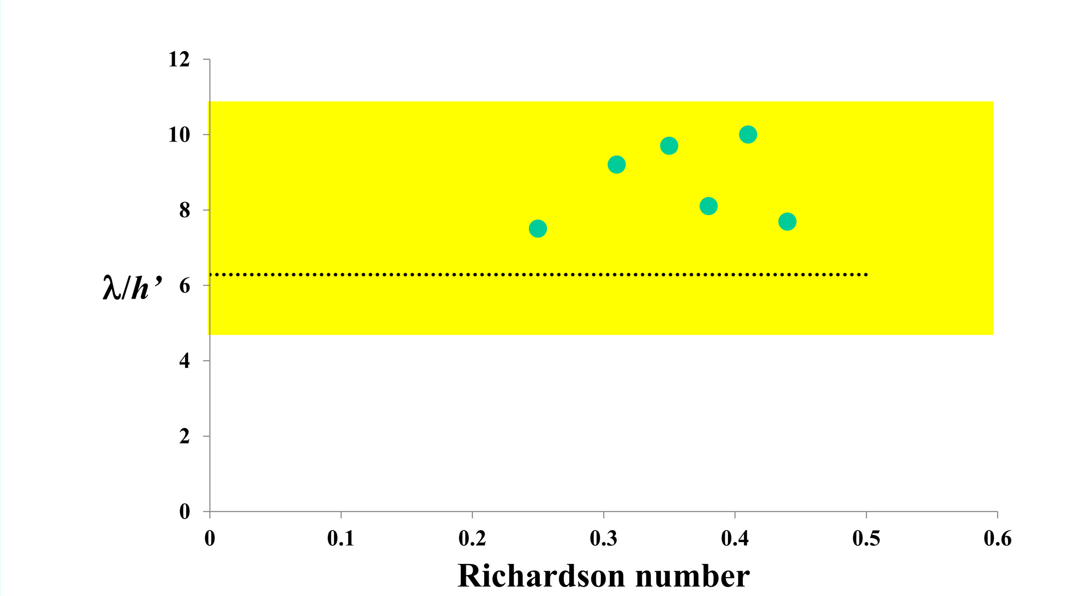
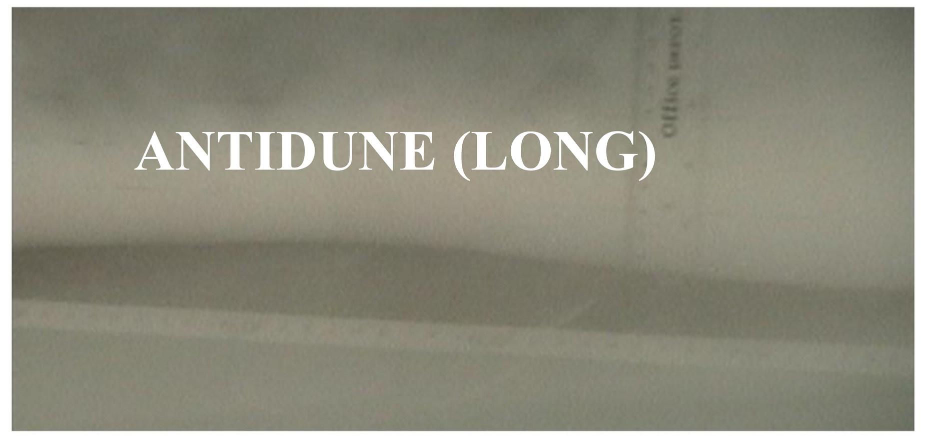


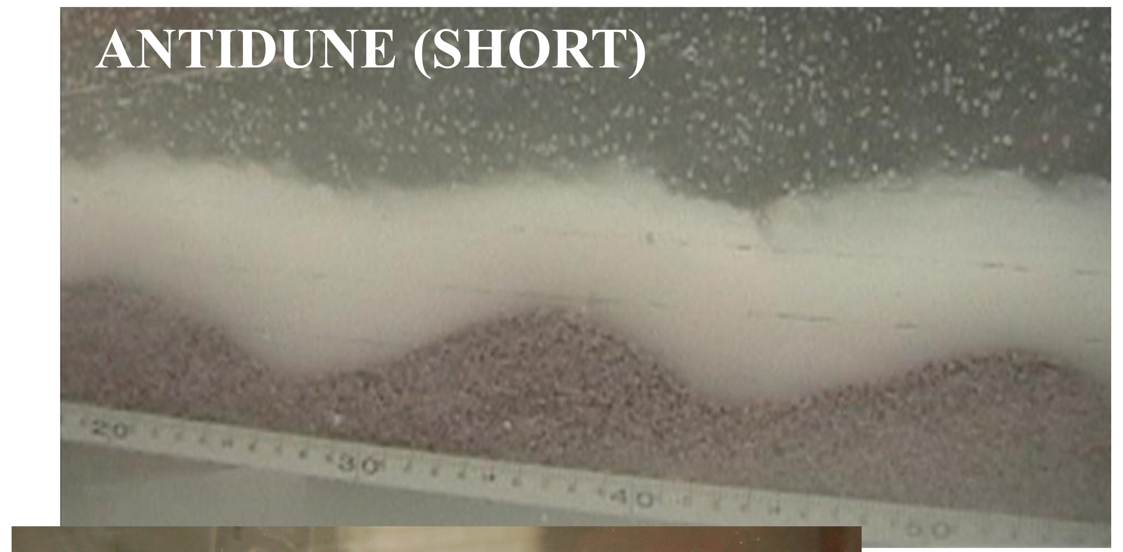
Figure above shows the ratio of dune wavelength to thickness of the wall layer, as function of Richardson (densimetric Froude) number. This figure summarizes one of our main results, and suggests that these bedforms might be effectively dunes, scaling with the thickness of flow closer to the bed for relatively high supercritical flows (yellow band indicates observed -field and laboratory data range for subaerial strteams)

There were cases in which bedforms that appeared to form as dunes, evolved and interacted strongly with the current interface, in particular for coarser sediments and for supercritical flows closer to critical conditions (Ri > 0.7-0.8). Since the final heights of these bedforms were comparable to the flow thickness, there was a strong bedform-interface interaction after the attain a certain height during their formation, and it appeared that bedform wavelength was then set by strong feedback mechanisms between the original bedform (similar to dunes) and current interface. These we described as a different bedform kind we called dune-antidune.

ANTIDUNES

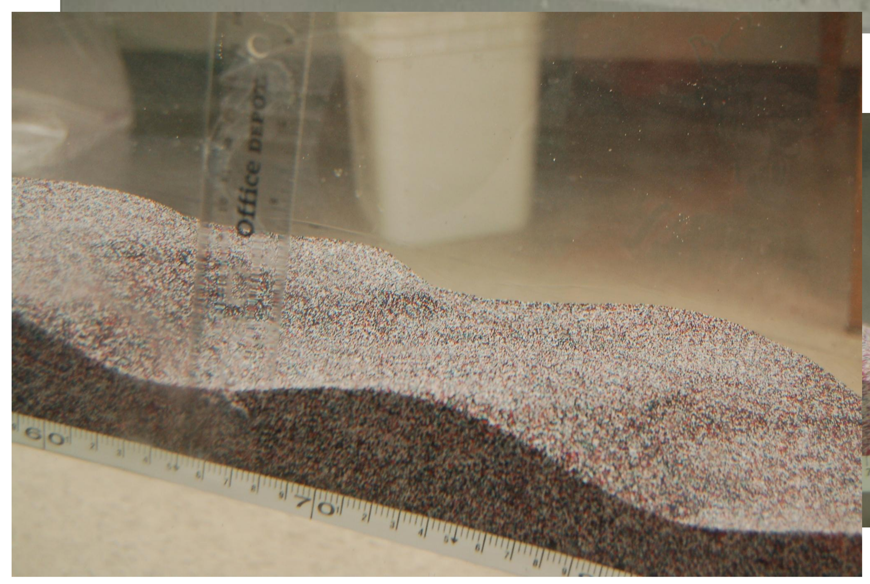


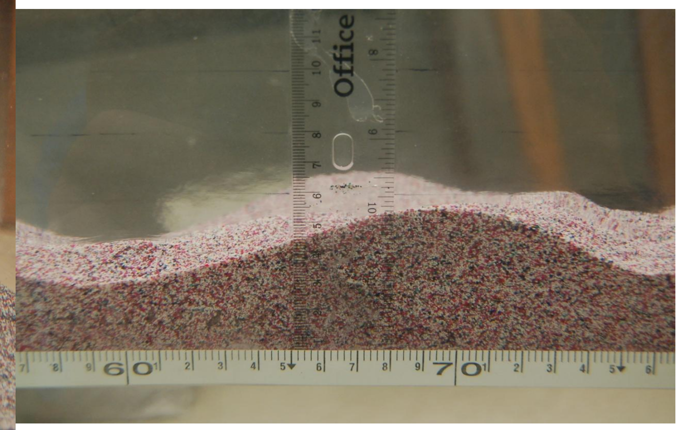
- Two different types of antidunes were observed to develop under supercritical conditions in our experimental runs: long wavelength and short wavelngth.
- Long-wavelength antidunes (wavelengths ranging 0.30-0.43 m) formed more commonly in the fine-grained sediments, but they were observed also to develop for the coarser sediments.
- Long antidunes formed for Richardson numbers larger than about 0.5 only. There were cases in which the bed configuration oscillated between short and long wavelength antidunes during initial stages of bed evolution. For these transitional cases, runs were purposely prolonged and it was observed that one bedform type prevailed, thus indicating the final equilibrium bed stage for the given flow conditions.
- Long-wavelength antidunes were symmetrical, in phase with current interface waves, with heights that did not surpassed 3 cm, and wavelengths ranging 7-10 times current thickness.
- Long antidunes behave mostly as standing or slightly upstream-migrating bedwaves, but in some cases they appeared to migrate downstream as well.



For the medium and coarser sediments tested, an interesting bedform that we believe has not been fully described before developed, for Richardson numbers that ranged between 0.4 to about 0.8. These bedforms were observed to originate as dunes (i.e. asymmetrical and with no current interface deformation during initial stages of bed development), but large bedform-height growth induced strong interaction and feedbacks with current interface. For these particular cases, bedforms developed heights of the order of the current thickness, evolved into a symmetrical bedwave with wavelengths slightly larger than dunes, but much shorter than the long antidunes. They were observed to migrate downstream (flow thickness was larger on the bedform trough and smaller on the bedform crest, see Figure to left).

Because of their strong interaction with current interface, we classify these bedforms as short-wavelength downstream-migrating antidunes.





We observed interesting feedback mechanisms between the bed and the current interface during the development of these features. The initially formed asymmetrical dune-like bedform evolved into a slightly longer, symmetrical, downstream-migrating bedwave with no visible flow separation after its crest. Their final wavelength appeared to be set at some intermediate value between that of the original dune-like feature, and that of a downstream-migrating antidune. It was evident from our visualizations that what originated the interface deformation (at the observed bedwave wavelengths) was the bedform itself, rather than other initially present interface undulations inherent to supercritical flows (which were of much longer wavelength).

This suggests that under these conditions, the bedform wavelength is set by the bed instability and further bed-interface feedbacks, rather than interface instability alone. In a few cases we observed that this downstream-migrating dune-antidune bedform reached a final asymmetrical shape, but in all cases the bedforms showed amplitudes comparable (or even larger) than the current thicknesses. Thus, the final heights and wavelengths appeared to be set by bed-interface interactions. We use these major distinctive elements to distinguish between the dune-antidune features and the true supercritical dunes described previously.

Deep-Water Bedform Phase Diagram – Density Currents

Graph to the right summarizes our experimental observations. It shows the bedform wave number formed with bedform wavelength and current thickness (scatter for dunes is in part a result of this choice of plotting, as thickness of wall layer is a more proper scaling for the bedforms we call DUNES). Current ongoing experiments show dunes also forming in the subcritical regime for density currents, but these require further analysis. Next: bedform regime for TURBIDITY CURRENTS!