Temporal Evolution of Ripple-Field Characteristics:
A Defect-Dynamic Approach

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LONG-TERM GOALS

I plan to develop a numerical model to investigate bedform evolution driven by defect dynamics; the aspects of bedform development and behavior that arise from intrinsically plan-view interactions involving crest terminations and bifurcations.

OBJECTIVES

This research is leading to a better understanding of how bedform wavelength and orientation change through time. This work will address how fields of wave-generated sub-aqueous ripples as well as wind-generated ripples and other kinds of bedforms evolve, under the highly variable wave forcing of inner continental shelf and terrestrial environments.

APPROACH

Werner and Kocurek (1997; 1999) introduced an analytical framework treating defect dynamics. However, the crucial processes involving the growth of new defects cannot be investigated in that framework, so I will develop a spatially-explicit numerical model to address how bedform patterns change, especially as forcing conditions vary temporally.

To develop empirical bases for the numerical treatment, I have: 1) conducted fieldwork (described below) involving eolian bedforms, with Philippe Claudin, Bruno Andreotti, Olivier Pouliquen, and Rebecca Hoyle; 2) begun a collaboration involving separate observations of subaqueous ripple evolution and sorted-bedform changes with Giovanni Coco and Malcolm Green; and 3) begun a collaboration to measure eolian megaripple evolution in the field and lab (along with a collaborative modeling effort) with Haim Tsoar and Hezi Yizhaq.

WORK COMPLETED

Several bedform researchers, chiefly Philippe Claudin, Bruno Andreotti, Olivier Pouliquen, Rebecca Hoyle, and myself conducted a week-long field campaign and workshop on bedform pattern evolution in Western Sahara. We discussed the respective roles that defect dynamics and more-traditional longitudinal-profile processes play in bedform evolution, and devised experiments to test the importance of the two. I will spend a month in 2006 working with Andreotti and Claudin in Paris.

I spent a month at the National Institute for Water and Atmospheric Research in New Zealand, collaborating with Giovanni Coco and Malcolm Green on alternative approaches to modeling large-

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scale, inner-shelf 'sorted bedforms' (Murray and Thieler, 2004; Murray et al., 2005) (Fig. 1). We also scrutinized tripod-mounted side-scan sonar observations they have collected concerning inner-shelf ripple evolution during a several-day wave event. We developed plans for how to analyze this data set to evaluate the role that defect dynamics played in the considerable pattern changes, and plans to use these observations to motivate the representation of defect-dynamic interactions in a numerical model to be developed.
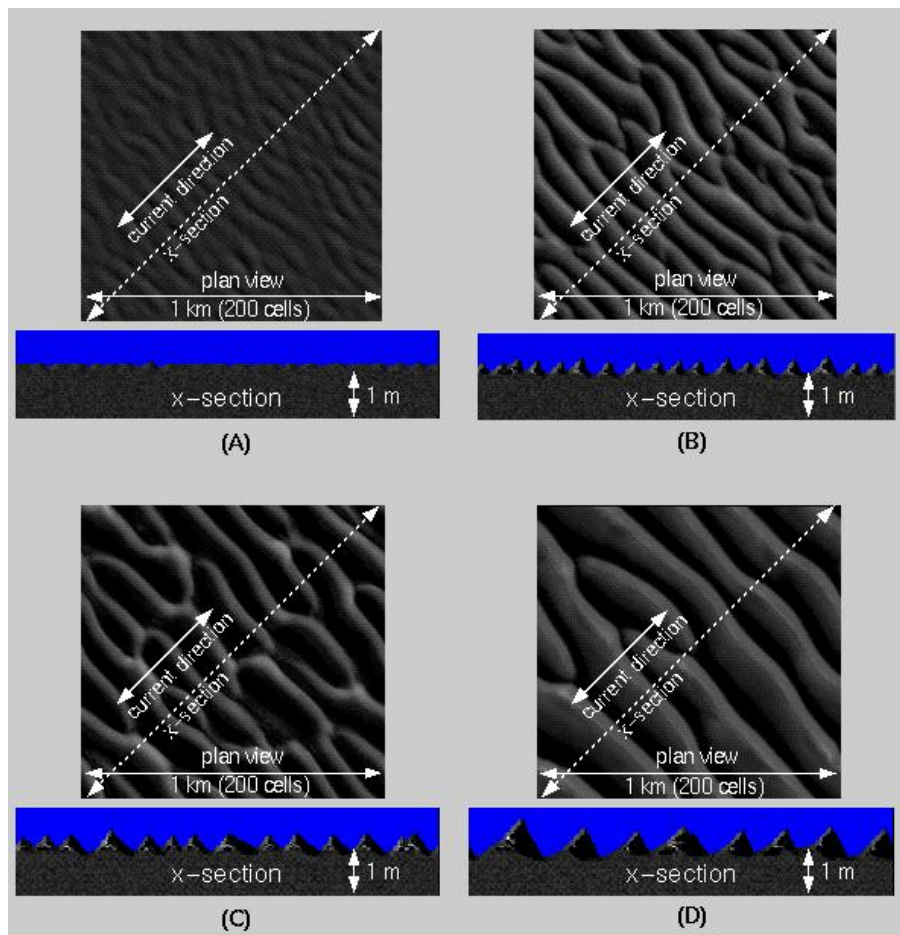

Figure 1. Output of the model of large-scale grain-size sorted patterns on inner continental shelves. Gray scale shows the grain-size composition, averaged over the top 15 cm of the bed in the plan view—black represents fine. The image shows 200 x 200 cells (1 km x 1 km). This simulation featured 2 m wave heights, 10 m water depth, and a 0.1 m/s current that reversed each day. Initial conditions consisted of a percentage of coarse material assigned independently for each cell randomly from a range of 0 to 40% coarse, and a flat bed. Grain sizes were 0.00015 and 0.001 m. (A) – (D) show progressive snapshots, illustrating wavelength coarsening and a corresponding decrease in the number of defects.

I have made considerable progress getting a collaboration with Israeli bedform researchers started concerning the key role that defect dynamics may play in the origin of the enigmatic phenomenon of eolian megaripples. Haim Tsoar, Hezi Yizhaq and I developed a proposal to the US-Israel Binational Science Foundation (BSF), to leverage the field observations described under Results below into more

considerable support to develop a more empirically grounded numerical model than the current funding alone would allow. The proposal received very strong reviews, suggesting that funding during the next cycle (2007), and more modest initial BSF support to get the field observations started in 2006, are realistic hopes.

RESULTS

The discussions and resulting field experiments in Western Sahara led to groundbreaking discoveries concerning eolian bedform evolution. To assess the importance of defect dynamics in wind-ripple development, we measured the initial plan-view characteristics of perturbations forming from a flattened bed, as well as the final dimensions of the well-developed ripples, and documented the evolution between the two. We discovered that the density of defects in the initial pattern decreases with wind strength. As would be expected within the defect-dynamic framework given this observation, we also discovered that the amount of wavelength increase, or 'coarsening' decreases with wind strength; wind-ripple fields coarsen by an order of magnitude under the mildest wind conditions observed (that caused sediment transport), and by only a factor of four for the strongest winds. In addition, we observed that the 'saturation,' or stabilization of the wavelength corresponds to the regional elimination of defects, again the relationship expected within the defect-dynamic framework. However, we did not gather any data that would preclude some currently unknown longitudinal-profile process from being a significant influence on this saturation.
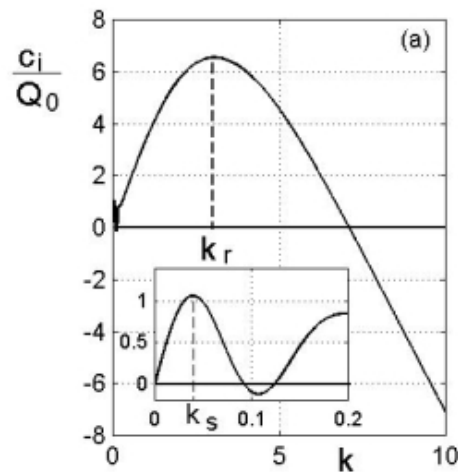

Figure 2 Graph: Linear stability analysis indicates the presence of two maxima in the growth rate curves. The first maximum pertains to ripples with wavelength with $\lambda_s = 157$ cm and the second (shown in the inset) to ripples with much a shorter wavelength $\lambda_r = 2.09$ cm.

At least as significant as the results of these experiments concerning wind ripples, experiments concerning the initiation and evolution of eolian megaripples produced results that will change the way researchers think about this phenomenon. The assumption has been that eolian megaripples are much larger than standard ripples because they arise from a different instability—one that favors a wavelength at least an order of magnitude larger (Fig. 2). No agreement has emerged concerning the nature of this hypothesized instability, but all the possibilities put forward involve the observational fact that megaripples only develop where mixed grain sizes are involved. However, we discovered that

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the characteristics of the initial perturbations that grow into megaripples did not differ from those that grow into standard ripples, throwing all previous work on this subject into serious doubt (Fig. 3). An alternative hypothesis for the large size of megaripples involves defect dynamics, and the continued injection of new defects into the pattern, allowing much more coarsening than occurs for standard ripple patterns. The proposed work with Haim Tsoar and Hezi Yizhaq will explore this hypothesis with field experiments, wind-tunnel observations, and numerical modeling.
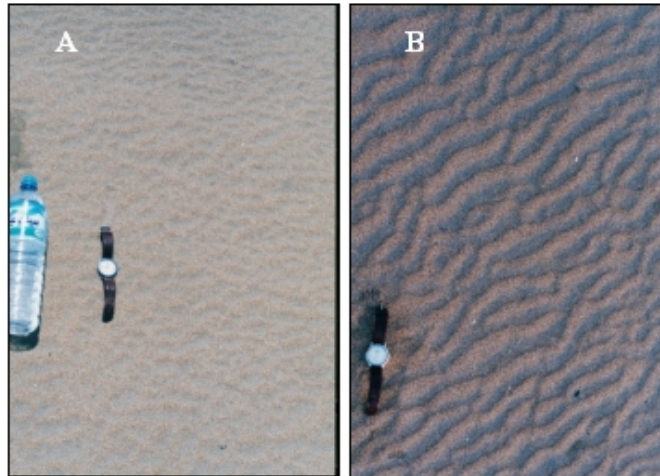

Figure 3. Photos of a field experiment show the early growth of megaripples from a flat bed at two different times. Dimensions of the initial perturbations are the same as for normal wind ripples

Rebecca Hoyle and I also conducted experiments designed specifically to provide empirical bases for a numerical defect-dynamic model. For example, we constructed defect-free ripple fields (with realistic profile characteristics) at various angles to the wind to determine how newly growing ripples would or would not interact with the pre-existing crests (e.g. Fig. 4).
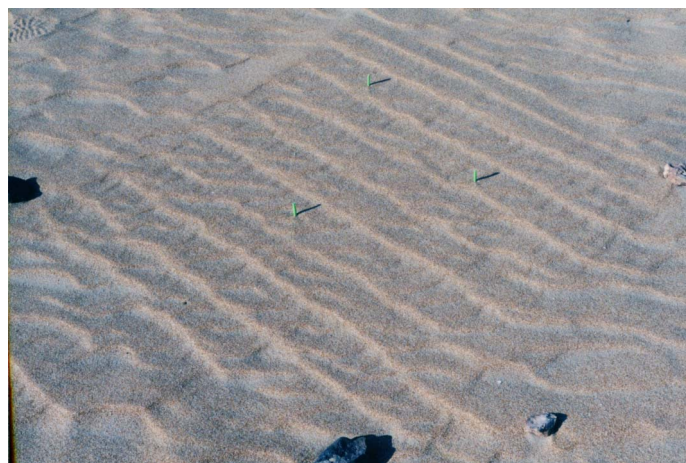

Figure 4. Photos of a field experiment showing how ripples growing at a moderate angle to preexisting crests can inject new defects, cutting the old crests in places.

IMPACT/APPLICATIONS

I expect that the observational and modeling work that is developing will lead to fundamental shift in our conception of bedform evolution. Almost certainly, researchers interested in eolian morphodynamics, and ultimately those studying bedforms of other types including on the seabed, will alter their thinking to include plan-view interactions as well as the longitudinal-profile perspective that has dominated previous work. The numerical modeling initiated as part of this project, which will involve these plan-view interactions explicitly, will lead to an improved predictive capability as well.

RELATED PROJECTS

An ongoing project involving the observation and modeling of large-scale, inner shelf sorted bedforms (Murray and Thieler, 2004; Murray et al., 2005) relates to the defect dynamic work in two ways: Defect dynamics are quite evident and important in the evolution of these previously enigmatic seabed features, and this model provides a ready-made numerical framework for investigating the role that defect dynamics have in the evolution of bedform patterns, including eolian megaripples, as is described in the following excerpt from the BSF proposal mentioned above:

A simple mathematical model of aeolian megaripples was recently introduced by Yizhaq (2004), which is based on the Anderson model (Anderson, 1987) and on the mechanism of 'fine fraction impact ripples'. The main idea is that the sediment consists of a mixture of sand grains with two different sizes and that the wind is not strong enough to cause the coarse fraction to saltate. The simplified model takes into account both saltation and reptation fluxes in the so-called Exner equation representing the conservation of mass. Spatial variability of saltation flux is due to sufficiently large undulations of the bed. In such cases, the saltation flux can depend on the bed topography such that it decreases at the windward face while increases at the leeward of the ripple. In these latter cases, the spatial variability of the flux of saltating grains, as well as the feedback of the bedform on the sand flux, must be taken into account. The variability of the saltation flux leads to space-time dependence of the number density of impacting grains on a flat surface, which makes the problem quite complicated. The initial work (Yizhaq, 2004) focused only on linearized dynamics, representing infinitesimal amplitude perturbations, and for simplicity assumed that the number density of impacting grains to be constant. It is a two scales model where spatial variations of the saltation flux dominates at large scales (order of meters (and for long times, while spatial variations of the reptation flux dominates on small scale (order of cms.) and for shorter time scale. Linear stability analysis indicates the presence of two maxima in the growth rate of the unstable modes. The gravest mode corresponds to megaripples and the other to ``standard" aeolian sand ripples. The model predicts that the megaripple wavelength is about several times the mean saltation hop length. Thus, one body of literature follows the hypothesis that the large wavelength of megaripples reflects an inherent length scale related to the characteristics of the saltating particles. In an alternative hypothesis applicable to many different kinds of bedforms, the wavelength of a bedform field tends to increase in time (coarsening) through interactions between individual bedforms (Murray and Ashton, 2003). In this hypothesis, the wavelength observed in nature reflects the length of time over which the patterns has been developing, and the availability of 'defects,' or imperfections in bedform crests, that facilitate mergers between individual crests (Werner and Kocurek, 1997;1999). In this scenario, the large wavelength of megaripples, relative to 'regular' aeolian ripples, reflects chiefly a longer lifetime for megaripples.

Although no models have been designed to test this second hypothesis for megaripple wavelength specifically, one of the PIs (Murray) recently developed a model of a type of bed pattern that is an analogous in many ways to megaripples. In this cellular model, which could be relatively easily adapted to investigate megaripple formation and evolution, the wavelength results from ongoing interactions within the bedform field, rather than being determined initially by a characteristic length. Murray and Thieler (2004) developed an exploratory model for the formation of 'rippled scour depressions,' which are large-scale bedform-like patterns on the seabed. These 'sorted bedforms,' like megaripples, are intimately associated with mixed grain sizes; the bed on many inner continental shelves is segregated into swaths of coarse material (coarse sand and gravel), separated by domains of fine sand. Coarse swaths, usually on the order of 100 m wide, often extend kilometers in the offshore direction. Sharp boundaries separate coarse and fine domains. The plan-view pattern can be quite well ordered, reminiscent of well-organized bedforms such as aeolian ripples and megaripples.

Murray and Thieler (2004) suggested that the formation and maintenance of these 'sorted bedforms' is due to an instability involving grain-size sorting. The wave-generated ripples that form where a shallow seabed is covered by coarse material increase the turbulence and shear stress, and thus would tend to inhibit the deposition of fine sediments, and further winnow more of the fine particles. The coarse lag then protects the material beneath from further entrainment, much as the armoring effect in aeolian megaripples. Their mathematical model based on sediment-transport formulae for the local fluxes of fine and coarse material that depend on the local bed composition, as well as on bed slope (as do the saltation and reptation fluxes in aeolian environments). In their numerical simulations a three dimensional grid of cells represents the bed, with grain size composition defined in each cell, although only sediment in cells nearest to the bed-surface at each horizontal location participate in sediment transport. The fluxes of the two size classes are computed separately at each time step. The numerical results show that sorted bedforms develop spontaneously, strongly resemble aeolian sand ripples in plan view, and that the main plan-view and profile characteristics are similar to the observed sorted bedforms. In addition this modeling approach, which treats the two fluxes separately, shows the vertical segregation scale of the bedforms (Murray and Thieler, 2004). (While this model addresses the formation of the large-scale sorted bedforms and does not explicitly simulate the formation of the wave-generated ripples, these ripples in the coarse domains also involve grain-size sorting and armoring of the crests; both the large-scale sorting and the meter-scale ripples bear striking similarities to aeolian megaripples.)

Although subaqueous transports mechanisms are considerably different than those in aeolian environments (mainly because the density difference between sand and water does not allow for saltating grains that effectively bombard the bed, and also because the direct action of the bottom shear stress due to the fluid flow is important), and although the scales of the sorted bedforms Murray and Thieler addressed are much larger than those of aeolian megaripples, the two phenomena share many important characteristics, and the Murray-Thieler model can be adapted to address aeolian megaripple formation.

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PUBLICATIONS

Published abstract: A. Brad Murray, 2005, Bedform pattern evolution in two horizontal dimensions: Extreme wavelength increases with mixed grain sizes, Geophysical Research Abstracts 7, 01859, SRef-ID: 1607-7962/gra/EGU05-A-01859.

HONORS/AWARDS/PRIZES

Invited, extended talk at the European Geosciences Union General Assembly, "Bedform pattern evolution in two horizontal dimensions: Extreme wavelength increases with mixed grain sizes," Vienna, 2005.