MODELLING THE ROLLOVERS OF SANDY CLINOFORMS FROM THE GRAVITY EFFECT ON WAVE-AGITATED SAND

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Abstract.

Clinoforms on coasts exposed to ocean waves form from sand exported from the shoreface during extreme wave conditions and deposited where wave action diminishes. Elsewhere, it is shown that, during upper 5-percentile wave conditions, wave-induced shear stresses exceed the sediment threshold of motion to below the clinoform rollovers. Experiments and theory suggest that, where bed sediments are agitated by waves, the effect of gravity should move particles down-slope with a flux proportional to the slope. Combined with considerations of continuity, this implies a diffusion of the sediment topography, a property that would explain the smooth seabed morphology found at sandy rollovers where recorded with multibeam sonar. For situations where this gravity effect dominates, a simple analytical expression developed here shows how the rollover curvature should relate to wave properties and to the offshore component of sediment flux. More sharply curved rollovers are expected where waves have short periods or where the sediment flux is large. Relative sediment fluxes were calculated using the model from rollover curvature and wave properties for sites from California, southeast Australia, and Atlantic and Mediterranean Iberia. The relative magnitudes of the fluxes are roughly as would be expected from local physiography and coastal erosion rates. For sandy clinoforms developed under mainly wave influences, the model could be useful for exploring variations within clinoform datasets (e.g., how varied convexity in an area of uniform wave properties reflects varied sediment flux) and for interpreting how varied curvatures of rollovers within seismic stratigraphy reflect how wave climate and flux have varied in the past.

Introduction

Diffusion transport models have been used to simulate the shapes of clinoforms (Flemings and Grotzinger 1997; Kaufman et al. 1991; Mitchell and Huthnance 2007; Rivenaes 1992, 1997; Schlager and Adams 2001; Syvitski and Daughney 1992) but are often difficult to justify from first principles because they strictly require that the sediment transport flux is exactly proportional to the bed gradient. For example, delta-front transport by slumps has been suggested to cause down-slope movement as required (Kenyon and Turcotte 1985) though fluxes from slope instability are likely to be nonlinear with gradient (Anderson 1994). However, the gravity effect on wave-agitated sand can potentially provide a flux proportional to gradient (Bailard and Inman 1981; Huthnance 1982a, 1982b; Mitchell and Huthnance 2007) so sandy clinforms could be more straightforward targets for modelling.

Estimating sediment fluxes in shelf seas is important for various civil engineering and academic applications. Modern sediment fluxes can potentially be estimated from tidal current and wave properties (Soulsby 1997) and fluxes to the littoral zone can sometimes be estimated from coastal and terrestrial erosion (Quartau et al. 2012). Seabed morphology also helps such estimates, for example, from tracking migrating sand dunes (Schmitt et al. 2007), though such estimates often have large uncertainties (van Landeghem et al. 2012). They are less useful for studying past fluxes because the migration often destroys much of the stratigraphic record of the dunes and dating methods do not have sufficient resolution. Although the method outlined here also has its own limitations, it could provide independent estimates to help that effort.

As surface gravity waves are created by wind shear, changes in wave climate of the past oceans are of potential interest for recovering climatic changes in meteorological conditions and have implications for rates of other processes, such as coastal erosion. Changes in global storminess have been inferred indirectly from incidence of sea salt and dust in ice cores (Fischer et al. 2007), but more site-specific past wave properties are lacking. This note was motivated partly because the procedure outlined here may help in reconstructing changes of wave properties in the geological past and could be combined with other methods, such as based on grain size (Dunbar and Barrett 2005; Pickrill 1983).

Mitchell et al. (2012) outlines various other types of currents besides wave orbital currents that potentially affect the rollovers of these sandy clinoforms, based on published current meter datasets and models from similar coasts. The gravity effect outlined herein is not claimed to act exclusively. Rather, assuming that the effect dominates can lead to some potentially useful results (bounds of sediment flux or wave properties). These results can then be compared with other evidence for support or refutation.

Datasets

The datasets and derivation of wave properties are described by Mitchell et al. (2012) and are outlined only briefly here. Figure 1 shows clinoform profiles from Mitchell et al. (2012) selected where information on sediment grain size was available. From left to right in Figure 1, the data were collected from the Oceanside area of southern California (Hogarth et al. 2007; Le Dantec et al. 2010), Malabar Coast of southeast Australia (Field and Roy 1984), Iberian Atlantic (Lobo et al. 2005; Hernández-Molina et al. 2000) and Iberian Mediterranean coast near Almería (Hernández-Molina et al. 2000). The sediment at these sites is mainly a medium to fine sand. Mitchell et al. (2012) also describes procedures used to estimate mean significant wave height H_s and average period of the upper 5-percentile wave conditions at these rollovers. These data were extracted from local wave buoy data or from deep-water wave properties in the ERA-40 reanalysis dataset (Caires and Sterl 2003; Caires et al. 2005) where the coast was exposed.

Contribution of the Gravity Effect to the Clinoform Curvature

Models for the gravity effect on sand have been outlined previously (Bailard and Inman 1981; Huthnance 1982a,1982b) and articles describing its experimental and theoretical basis were summarized in the electronic supplement to Mitchell and Huthnance (2007). The effect has been observed in experiments with longitudinal tiltable flumes (Damgaard et al. 1997) as an increase in sediment flux when the flume was tilted so that the flow was “down-hill” and a reduced flux when it was tilted so that flow was “up-hill”. A steady current carries sediment in the direction of the current modified modestly by this gravity effect. However, where the current oscillates so that it has no residual, the gravity effect should dominate the sediment transport flux.

Theoretical and experimental measurements of bedload on slopes transverse to the current suggest that the parameter linking sediment flux to gradient should vary between $|u|^1$ or $|u|^3$ (Mitchell and Huthnance 2007), where $|u|$ is the peak oscillating current magnitude from waves. Detailed explanation is left to the earlier papers on this, but the arguments of Bagnold (1963) for a fully developed bedload produced by a steady current are helpful for visualizing the process. He suggested that the work done in opposing the effects of bedload grain—grain collisions by the current should be proportional to the power dissipation of the current multiplied by an efficiency factor. As the current's power dissipation for a horizontal bed is the shear stress (proportional to $|u|^2$) multiplied by its speed (proportional to $|u|^1$), this leads to sediment flux being proportional to $|u|^3$. Alternatively, the flux can almost be derived by considering the mechanics of the mobilized layer (Nielsen 1992). The flux depends on both the mean speed of particles in the layer but also on the thickness (or mass per unit bed area) of sediment mobilized by the current, which depends on the extent to which an effective dispersive pressure at the base of the bedload layer can maintain grains in saltation. The dispersive pressure is related to the shear stress acting on the layer multiplied by the sediment's angle of internal friction. Thus the dispersive pressure (and mass per unit area of particles mobilized) is proportional to the shear stress imposed by the mobilizing current (which is proportional to $|u|^2$). As bedload particle speeds in experiments follow the current speed (Meyer-Peter and Müller 1948), the net effect is of flux proportional to $|u|^3$. Although these arguments are for the flux directly arising from a horizontal current, these effects apply to the gravity component of flux on a gradient also. Unfortunately there have been too few measurements on longitudinal slopes to determine the exact exponent on $|u|$ for up-and-down slope agitation, which may in any case vary with the degree of development of the bedload, so the $|u|^2$ is adopted here as within the range of variation (Mitchell and Huthnance 2007), though up to $|u|^3$ may be possible.

The one-dimensional sediment flux (in the offshore distance x) can be written:

$$Q = K\frac{\partial z}{\partial x} \quad (1)$$

where Q (kg/m/s) is the down-slope mass flux per unit width of slope, K is a parameter set equal to $\zeta|u|^n$ and $-\partial z/\partial x$ is the topographic gradient of the bed (z is water depth, i.e., positive downwards). Parameter ζ (kg/m^{n+1}/s^{n+1}) represents the efficiency by which the wave-current agitation leads to a flux Q on a particular gradient. It cannot as yet be quantified as too few experiments are available, though it is suspected not to vary much for sediment of the same grain size and composition.

When combined with a relation to account for continuity (conservation of mass requires that a lateral change in Q must be accompanied by erosion or deposition on the seabed), Equation 1 leads to a diffusion equation in the topography of the sediment (Culling 1960). Diffusion of a property often smooths out or attenuates variability in that property. Multibeam sonar data recorded off Oceanside (Hogarth et al. 2007), south Iberia (Fernández-Salas et al. 2009) and Almería (Mitchell et al. 2012, their Figure 4) reveal that those sandy clinoforms are indeed quite smooth, as expected from diffusion. Although not unique to the process described here, this is supporting evidence.

The morphology is assumed to be in a steady state. Where most deposition occurs on the clinoform face (Figure 2), the time-averaged offshore flux Q varies little going across the rollover. From Equation 1, uniform Q implies that K should then vary inversely with the offshore-steepening bed gradient, $\partial z/\partial x$. The analysis can be simplified by using the deep-water approximation for wave-induced water movements, because the distortion due to shoaling of waves is not so great at these water depths (in practice, this will somewhat underestimate the variation in $|u|$ with depth). The oscillating wave-current magnitude would then vary with depth according to (e.g., Masselink and Hughes 2003):

$$|u| = \frac{\pi H_s}{T} \exp\left(-\frac{4\pi^2 z}{gT^2}\right) \qquad (2)$$

Substituting Equation 2 in Equation 1 with $K = \xi |u|^n$ leads to:

$$\frac{\partial z}{\partial x} = \frac{Q}{\xi}\left(\frac{T}{\pi H_s}\right)^n \exp\left(\frac{4\pi^2 n z}{gT^2}\right) \qquad (3)$$

Figure 3A was produced using a simple finite-difference evaluation of Equation 1 in which sand was supplied from the left boundary at constant flux Q_0 and K declined exponentially with depth as expected from Equation 2, while continuity (conservation of mass) was maintained to derive the changes in bed topography. The steepening across the rollover expected from this calculation (which does not assume uniform Q) is less abrupt than some of the profiles in Figure 1, a hint that not all transport and deposition follows the scheme described herein. The model surface is also asymptotic with sea level, in contrast to the seabed landward of the rollovers in Figure 1 at finite depth, because the model neglects suspension under breaking waves and other processes operating in shallower water.

Two further models are shown in Figure 3. Figure 3B was produced by running the model onto a ramp that steepens abruptly by a factor of five along the profile. The predicted surface topography is more tightly curved than in Figure 3A, showing that pre-existing topography can influence the rollover morphology (besides other sediment transport and deposition processes around basement features (Mitchell et al. 2012)). In Figure 3C, the exponential parameter varying *K* with depth was doubled abruptly half way through the model run. It shows that the rollover curvature approaches a steady-state geometry relatively quickly after the change.

For the purely steady-state case, the curvature of the rollover topography is obtained by further differentiating Equation 3:

$$\frac{\partial^2 z}{\partial x^2} = \frac{Q}{\zeta}\left(\frac{T}{\pi H_s}\right)^n \frac{4\pi^2 n}{gT^2}\exp\left(\frac{4\pi^2 nz}{gT^2}\right)\frac{\partial z}{\partial x} \qquad (4a)$$

or

$$\frac{\partial^2 z}{\partial x^2} = \left(\frac{Q}{\zeta}\right)^2\left(\frac{T}{\pi H_s}\right)^{2n} \frac{4\pi^2 n}{gT^2}\exp\left(\frac{8\pi^2 nz}{gT^2}\right) \qquad (4b)$$

From Equation 4b, rollover curvature would be expected to increase with increasing *Q*, with decreasing *T* (if the exponential term dominates) and with decreasing H_s. Curvature should increase with depth, a feature of the model in Figure 3, but not of all profiles in Figure 1. If *Q* were not uniform but declined significantly across the rollover because of deposition, Equation 3 suggests that the bed gradient will decline more gradually and the curvature of the rollover should be smaller than calculated assuming uniform *Q*, hence Equation 4 is an upper bound.

Seabed gradient and curvature were estimated from second-order polynomials (Wessel and Smith 1994) fitted to the bathymetry profiles in Figure 1 as shown by the red curves, to 200 m either side of the rollover points (solid circles). The relative values of *Q* for the different sites were then evaluated from the bed gradient at the rollover Equation 3 and its curvature Equation 4b assuming n = 2 and with the wave properties (T, H_s) associated with upper 5-percentile conditions in Mitchell et al. (2012). The resulting values shown below the profiles in Figure 1 are relative values because ζ is unknown.

Some of the trends in Q are as expected from the local physiography of each area. For example, the smaller Q of the second Oceanside profile compared with the first could be due to sediment trapped by Scripps Canyon lying immediately south of the second profile (Le Dantec et al. 2010). Within the group of SE Australian profiles, the first (D of Field and Roy (1984)) lies within a bay whereas the other three lie off a headland, hence the (on average) greater flux of the latter would be consistent with proximity of the coastline and stronger currents. The large value for the first Faro profile seems anomalous, although this profile (Figure 8 of Lobo et al. 2005) lies offshore a major spit at a major change in orientation of the coast so rapid sand export is possible here. The smaller value for the second Faro profile arises because the coast is southeast facing (Hernández-Molina et al. 2000), away from the main “weather” from the Atlantic Ocean. The values for the Mediterranean profile would seem rather high given the shorter wave period of the sea there (Mitchell et al. 2012). The polynomial actually underrepresents the rollover curvature, so the model-calculated Q should be larger. A headland location of this profile may explain the high values or perhaps a coastal current.

As mentioned earlier, the configuration or gradient of the pre-existing surfaces underlying these clinoforms may have influenced these rollovers (i.e., as expected from Figure 3B). The pre-existing surfaces are shown in gray in Figure 1. All of the SE Australia underlying surfaces have similar gradients so other explanations (such as varied Q given above) are needed to explain their varied curvatures. Similarly, the other differences in Q in Figure 1 are difficult to explain by varied gradient of their underlying surfaces. However, the Almería clinoform was deposited on an exceptionally steep surface, which may have contributed to the sharp curvature of its rollover. Hence the steady-state Q value for this site may well be overestimated in Figure 1 compared to the other sites, partly explaining this anomaly.

Seismic stratigraphy involves interpreting the configurations of strata imaged seismically to deduce the geological history and processes occurring within an area. The modelling shown here illustrates that flux and wave climate could influence the profile shape of the clinoform deposit. In Mitchell and Huthnance (2007), we also investigated how a model with a power-law variation in oscillating currents with depth (which represented the combined effect of modern tidal and other currents about the USA Atlantic shelf edge) produces a different shape. Unfortunately, these models suggest that it will not be possible to use the rollover shape in seismic data to discriminate these wave-influenced clinoforms from other types, such as river-mouth deposits (Friedrichs and Wright 2004; Pirmez et al. 1998), which have similar shapes. Other discriminators are needed, such as presence or otherwise of channels upstream of the rollover.

At present the above observations are the only indicators available with which to assess the model. A better test would involve a more complete assessment of sediment fluxes (Inman 2003), in particular using sediment accumulation rates on the clinoform foresets such as from vibracores. Nevertheless, the order of values is generally plausible, suggesting that the model could also be useful for investigating the wave-climate origin of varied rollover curvature in seismic stratigraphy, particularly where other proxies of wave climate are available for verification, such as from sediment texture (Dunbar and Barrett 2005; Pickrill 1983). Estimates of Q would be needed from foreset accumulation data, allowing combinations of T and H_s to be recovered. Modern wave conditions (T, H_s) and the estimate of most recent Q would be used to calibrate Equation 3, i.e., place a value on ζ.

Conclusions

The rollover shape is similar to its shape produced by diffusion transport models in which the mobility parameter K is allowed to decline with depth, representing declining oscillating currents. Where mapped with sonars, these sandy clinoform rollovers indeed have smooth surfaces, as expected if diffusion of topography were occurring. The gravity effect on particles oscillated by waves or moved by along-slope currents will contribute to diffusion of the topography. A simple analytical expression was developed to show how profile curvature of the rollover relates to the wave properties and sediment flux if the gravity effect dominates and the morphology has reached a steady state. Although other influences on these rollovers cannot be ruled out, the relative predicted fluxes are plausible, suggesting that it could be useful in evaluating primary influences. These results also hint that variations in rollover curvatures in seismic stratigraphy could be used to estimate variations in wave climate of the past.

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References

ANDERSON, R.S., 1994, Evolution of the Santa Cruz mountains, California, through tectonic growth and geomorphic decay: Journal of Geophysical Research, v. 99, p. 20,161-20,179.

BAGNOLD, R.A., 1963, Mechanics of marine sedimentation, *in* Hill, M.N., ed., The Sea, vol. 3: New York, Wiley, p. 507-528.

BAILARD, J.A., and INMAN, D.L., 1981, An energetics bedload model for a plane sloping beach: local transport: Journal of Geophysical Research, v. 86, p. 2035-2043.

CAIRES, S., and STERL, A., 2003, Validation of ocean wind and wave data using triple collocation, Journal of Geophysical Research, v. 108, Paper C3098, doi:3010.1029/2002JC001491.

CAIRES, S., STERL, A., and GOMMENGINGER, C.P., 2005, Global ocean mean wave period data: Validation and description, Journal of Geophysical Research, v. 110, Paper C02003, doi:02010.01029/02004JC002631.

CULLING, W.E.H., 1960, Analytical theory of erosion: Journal of Geology, v. 68, p. 336-344.

DAMGAARD, J.S., WHITEHOUSE, R.J.S., and SOULSBY, R.L., 1997, Bed-load sediment transport on steep longitudinal slopes: Journal of Hydraulic Engineering, v. 123, p. 1130-1138.

DUNBAR, G.B., and BARRETT, P.J., 2005, Estimating palaeobathymetry of wave-graded continental shelves from sediment texture: Sediimentology, v. 52, p. 253-269.

FERNÁNDEZ-SALAS, L.M., DABRIO, C.J., GOY, J.L., DÍAZ DEL RÍO, V., ZAZO, C., LOBO, F.J., SANZ, J.L., and LARIO, J., 2009, Land—sea correlation between Late Holocene coastal and infralittoral deposits in the SE Iberian Peninsula (Western Mediterranean): Geomorphology, v. 104, p. 4-11.

FIELD, M.E., and ROY, P.S., 1984, Offshore transport and sand-body formation — evidence from a steep, high-energy shoreface, southeastern Australia: Journal of Sedimentary Petrology, v. 54, p. 1292-1302.

FISCHER, H., SIGGAARD-ANDERSEN, M.-L., RUTH, U., RÖTHLISBERGER, R., and WOLFF, E., 2007, Glacial/interglacial changes in mineral dust and sea-salt records in polar ice cores: Sources, transport, and deposition: Reviews of Geophysics, v. 45, paper RG1002, doi:10.1029/2005RG000192.

FLEMINGS, P.B., and GROTZINGER, J.P., 1997, STRATA: freeware for analysing clastic stratigraphic problems: GSA Today, v. 6(12), p. 1-7.

FRIEDRICHS, C.T., and WRIGHT, L.D., 2004, Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths: Coastal Engineering, v. 51, p. 795-811.

HERNÁNDEZ-MOLINA, F.J., FERNÁNDEZ-SALAS, L.M., LOBO, F., SOMOZA, L., DÍAZ DEL RÍO, V., and ALVEIRNHO DIAS, J.M., 2000, The infralittoral prograding wedge: a new large-scale progradational sedimentary body in shallow marine environments: Geo-Marine Letters, v. 20, p. 109-117.

HOGARTH, L.J., BABCOCK, J., DRISCOLL, N.W., DANTEC, N.L., HAAS, J.K., INMAN, D.L., and MASTERS, P.M., 2007, Long-term tectonic control on Holocene shelf sedimentation offshore La Jolla, California: Geology, v. 35, p. 275-278.

HUTHNANCE, J.M., 1982a, On one mechanism forming linear sand banks: Estuarine, Coastal and Shelf Science, v. 14, p. 79-99.

HUTHNANCE, J.M., 1982b, On the formation of sand banks of finite extent: Estuarine, Coastal and Shelf Science, v. 15, p. 277-299.

INMAN, D.L., 2003, Littoral cells. In: Schwartz M (ed) Encyclopedia of coastal science. Kluwer Academic Publishers, Dordrecht, Netherlands.

KAUFMAN, P., GROTZINGER, J.P., and MCCORMICK, D.S., 1991, Depth-dependent diffusion algorithm for simulation of sedimentation in shallow marine depositional systems, *in*

Franseen, E. K., Watney, W. L., St. C. Kendall, C. G., and Ross, W., Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition: Kansas Geological Survey, Bulletin 233, p. 489-508.

KENYON, P.M., and TURCOTTE, D.L., 1985, Morphology of a delta prograding by bulk sediment transport: Geological Society of America Bulletin, v. 96, p. 1457-1465.

LE DANTEC, N., HOGARTH, L.J., DRISCOLL, N.W., BABCOCK, J.M., BARNHARDT, W.A., and SCHWAB, W.C., 2010, Tectonic controls on nearshore sediment accumulation and submarine canyon morphology offshore La Jolla, Southern California: Marine Geology, v. 268, p. 115-128.

LOBO, F.J., FERNÁNDEZ-SALAS, L.M., HERNÁNDEZ-MOLINA, F.J., GONZÁLEZ, R., DIAS, J.M.A., DÍAZ DEL RÍO, G., and SOMOZA, L., 2005, Holocene highstand deposits in the Gulf of Cadiz, SW Iberian Peninsula: A high-resolution record of hierarchical environmental changes: Marine Geology, v. 219, p. 109-131.

MASSELINK, G., and HUGHES, M.G., 2003, Introduction to coastal processes and geomorphology. Arnold, London, 354 p.

MEYER-PETER, E., and MÜLLER, R., 1948, Formulas for bedload transport, paper presented at 2nd Congress, International Association for Hydraulics Research, Stockholm.

MITCHELL, N.C., and HUTHNANCE, J.M., 2007, Oceanographic currents and the convexity of the uppermost continental slope: Journal of Sedimentary Research, v. 78, p. 29-44.

MITCHELL, N.C., MASSELINK, G., HUTHNANCE, J.M., FERNÁNDEZ-SALAS, L.M., and LOBO, F.J., 2012, The depths of modern sand clinoforms: Journal of Sedimentary Research, this volume.

NIELSEN, P., 1992, Coastal bottom boundary layers and sediment transport: Advanced Series on Ocean Engineering, vol. 4: Singapore, World Scientific Publishing.

PICKRILL, R. A., 1983, Wave-built shelves on some low-energy coasts, Marine Geology, v. 51, p. 193-216.

PIRMEZ, C., PRATSON, L.F., and STECKLER, M.S., 1998, Clinoform development by advection—diffusion of suspended sediment: Modeling and comparison to natural systems: Journal of Geophysical Research, v. 103, p. 24,141-24,157.

QUARTAU, R., TEMPERA, F., MITCHELL, N.C., PINHEIRO, L.M., DUARTE, H., BRITO, P.O., BATES, C.R., AND MONTEIRO, J.H., 2012, Morphology of Faial Island's shelf: The results of volcanic, erosional, depositional and mass-wasting processes, Geochemistry Geophysics Geosystems, v. 13, Paper Q04012, doi:10.1029/2011GC003987.

RIVENAES, J.C., 1992, Application of a dual-lithology, depth dependent diffusion equation in stratigraphic simulation: Basin Research, v. 4, p. 133-146.

RIVENAES, J.C., 1997, Impact of sediment transport efficiency on large-scale sequence architecture: results from stratigraphic computer simulation: Basin Research, v. 9, p. 91-105.

SCHLAGER, W., and ADAMS, E.W., 2001, Model for the sigmoidal curvature of submarine slopes: Geology, v. 29, p. 883-886.

SCHMITT, T., MITCHELL, N.C., and RAMSAY, A.T.S., 2007, Use of swath bathymetry in the investigation of sand dune geometry and migration around a near shore 'banner' tidal sandbank. In: Balson, P.S., Collins, M.B. (eds) Coastal and Shelf Sediment Transport, Geological Society London, Special Publication 274, p. 53-64

SOULSBY, R., 1997, Dynamics of Marine Sands, A Manual for Practical Applications: London, Thomas Telford Ltd., 249 p.

SYVITSKI, J.P.M., and DAUGHNEY, S., 1992, DELTA2: Delta progradation and basin filling: Computers & Geosciences, v. 18, p. 839-897.

Van Landeghem, K.J.J., Baas, J.H., Mitchell, N.C., Wilcockson, D. and Wheeler, A.J., 2012. Reversal of sediment wave migration in the Irish Sea, NW Europe: A reappraisal of the validity of geometry-based predictive modelling and assumptions: Marine Geology, v. 295—298, p. 95-112.

Wessel, P., and Smith, W.H.F., 1991, Free software helps map and display data: Eos, Transactions, American Geophysical Union, v. 72, p. 441.

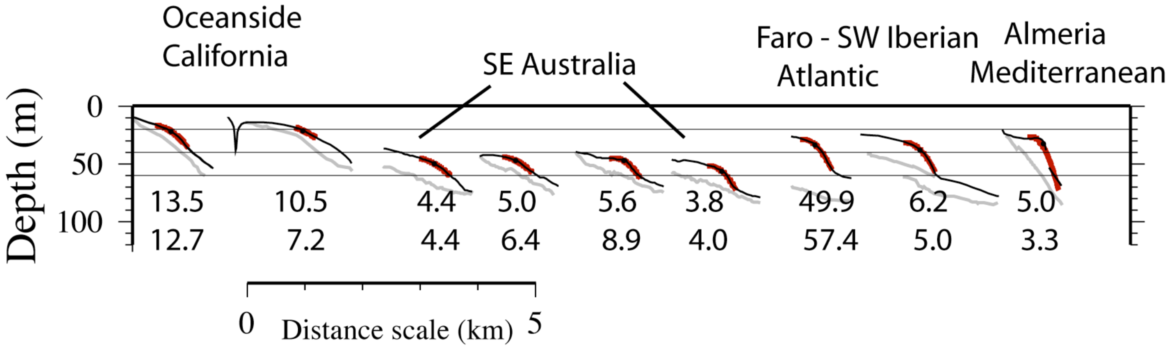

Fig. 1. Topographic profiles of near-shore sand bodies are shown with a 20:1 vertical exaggeration adapted from Mitchell et al. (2012). Solid circles locate the rollover points. Red curves underlying the data profiles are quadratic curves fitted to the data used to calculate gradients and curvatures at the rollovers. Gray lines represent the underlying surface over which the clinoforms have been deposited. Values shown beneath each profile are relative sediment flux calculated from bed gradient (upper row) and curvature (lower row) at the rollovers and wave properties by inverting Equations 3 and 4b. The profiles shown are (from left to right) D1 and D2 of Hogarth et al (2007), D, K, N, and R of Field and Roy (1984), Figure 8 of Lobo et al. (2005), and Figure 4 and 3 of Hernández-Molina et al. (2000).

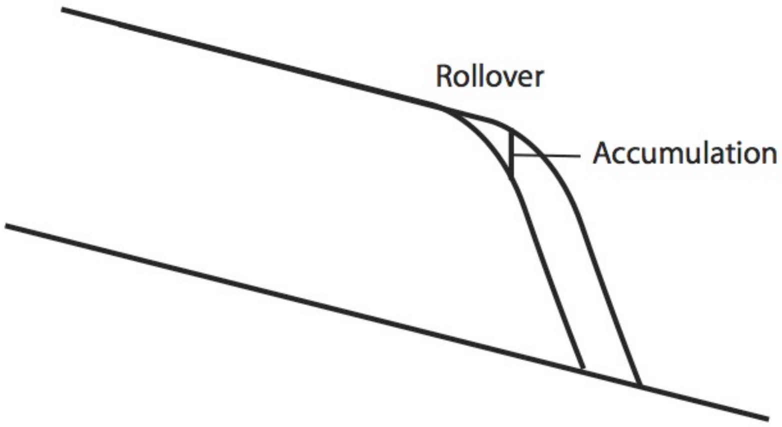

Fig. 2. Geometry of a prograding clinoform. In order to maintain the clinoform shape over time, deposition rates increase abruptly seawards over the rollover, as illustrated here by the difference between the two successive elevation profiles of the clinoform surface. If most of the newly deposited sediment lies on the clinoform face, a uniform time-averaged transport flux can be assumed across the curved portion (rollover) to maintain steady state morphology.

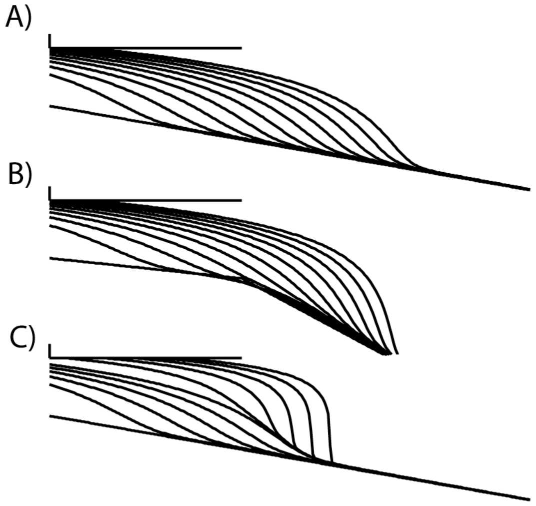

Fig. 3. Numerical model for development of a clinoform rollover obtained by evaluating Equation 1 with exponentially declining *K* with depth (Mitchell and Huthnance 2007), simulating the effect of wave action on sediment supplied from the left side of the model. A)

Sediment exported onto a simple linear ramp. B) Sediment exported onto a ramp that increases in gradient by a factor of five half way along the profile. C) Sediment exported onto a ramp with the exponential parameter (varying *K* with depth) doubled at half the model run.