Symmetrical convergent bedload sand transport pattern associated with headlands: A preliminary indication from bedforms, sediment distribution and bathymetry

Alex, C. BASTOS[1,2]; Neil, H. KENYON[1] and Michael, B. COLLINS[1]

[1]Southampton Oceanography Center
Empress Dock, Southampton,
SO14 3ZH, UK
Fax.: (44)23 593059
Email: acb4@soc.soton.ac.uk
[2] CNPq scholarship, Brazilian government

Abstract
Bathymetric, hydrodynamic and side-scan sonar data were reviewed in order to investigate the continental shelf sedimentary processes associated with a headland. The headland considered is the Isle of Portland (Dorset southern UK), where tidally-induced residual eddies are identified and used to explain the existence of a notable bank only on one side of the headland (Shambles Bank) (Pingree, 1978). A preliminary interpretation reveals that, in fact, there is a complex suite of bedforms, including sand banks and sand shoals, on both sides of the headland, with a fairly symmetrical distribution. The existence of this suite of bedforms appears to be associated with net bedload convergent transport patterns, on both sides of the headland. Instead of residual circulation, the transient nature of the flow during the tidal cycle (transient eddies), should be controlling the bedload transport patterns, and, as a consequence, the formation and maintenance of the sedimentary deposits. Part of the little asymmetry of the deposits, including morphology, is due to the greater influence of waves on the west side of the headland.

Introduction
A model to predict sand bank formation should integrate water movement and sediment transport, however, most of the models consider only the hydrodynamic process. Therefore, in the absence of a sediment transport model, this paper reviews the bedload sediment transport pattern associated with a headland, based on the seabed morphology, the spatial bedforms distribution, including a sand bank, and their relation to tidal current strength. The study area is the continental shelf around the Isle of Portland in Dorset, southern UK.

It must be considered that this discussion presents the first results concerning the detailed sediment and bedform dynamics associated with headlands; and that, the investigation aims to characterise, regionally and locally, the processes of evolution and maintenance of the sedimentary deposits.

1. Data Sets
In order to review the sedimentary processes around the Portland Headland, bathymetric, hydrodynamic, sediment grain size and geophysical (side-scan sonar) data sets are considered.

Seabed morphology were mapped through the UK Hydrographic Office sounding sheets, providing a high resolution bathymetric map of the seafloor around Portland. The bathymetric map produced, is based on more then a hundred thousand sounding points. Sediment and bedform distribution were characterised by existing maps of the seafloor, based on side-scan sonar data and bottom samples (Nunny, 1995 and, Kenyon, 1994). Hydrodynamic information is limited to the Tidal Stream Atlas (Hydrographic Office, 1973) and to 2-D hydrodynamic numerical models (Maddock and Pingree, 1978 and output from Mike-21 model, provided by Associated British Ports and from TELEMAC model, provided by HRWallingford).

2. The Continental Shelf around Portland
Pingree (1978), identified tidally-induced residual eddies around the Isle of Portland (Dorset – southern UK) using a numerical model, and explained the existence of a notable bank only on one side of the headland (Shambles Bank), using the tidal stirring concept described briefly above. The author calculated the Rossby number (R=1) for the Portland Headland, and showed that under this condition, clockwise flows do not have pressure gradient forces, resulting in a no tendency of bank formation on the eastern side of the headland.

The formation of a sand bank is associated with accumulation of sand, which is, in fact, a response of the regional sediment transport pattern and gradients in the transport rates. Thus, mapping the seabed morphology around Portland and comparing with the distribution of sediments and bedforms, not only the Shambles Bank was observed, but in fact, a quite symmetrical suite of sedimentary deposits and bedforms were mapped on both sides of Portland (Fig.1).

The shelf morphology around Portland is characterised by sedimentary deposits and by some areas of erosive bottom. Seabed sediments, over the area, consist of a discontinuous veneer of coarse lag deposits, associated with mobile sand sheets and bedrock outcrops. The sediment thickness is shown in a very generalised map (BGS, 1983) to be less than 0.5m. Exceptions are the sand bank and shoal areas.

The presence of sand shoals and sand banks, providing a remarkably symmetrical arrangement of sedimentary deposits around the headland, is associated with sand distribution patterns. The distribution of sand is, basically, restricted to the region of shoals and banks; exception is made for inner regions of Weymouth Bay, covered by a fine sand sheet and for central areas of Lyme Bay where a thin fine sand sheet occurs (Fig.2).

Sand shoals are observed on both sides of the headland; Adamant Shoal, to the east; and West Shoal, to the west. These shoals are aligned parallel to the coastline, in a concave-southward arcuate form. In general, they are 5 to7 m thick, reaching 10m beneath larger bedforms. Transverse bedforms are observed over these deposits. The larger bedforms described are sandwaves, showing wavelengths ranging from 100 to 300m and heights up to 5m (Nunny, 1995).

Although the sand shoals are similar in terms of their morphology, bedforms and thickness, the “banks” are quite different. The Shambles Bank, to the east of Portland, is associated with the Adamant shoal. The bank is 20m high and 5km long with sandwaves lying on its flank. The sandwaves, of between 5m and 10m in height and 300m in wavelength, show a convergent sand transport towards the crest of the bank. To the west of Portland, there is no bank comparable to the Shambles. However, the occurrence of a minor bank, or another shoal (Portland Shoal), associated with the West shoal, determines that both areas are under a similar process of sand transport.

3. Discussion

Tidal eddies are generated by a bottom frictional torque, induced by increased velocities near headlands, and producing vorticity in the flow leaving the headland (Pingree and Maddock, 1979; Robinson, 1983; Zimmerman, 1980; Geyer and Signell, 1990). The formation of sand banks by tidal stirring of the seas, was proposed by Pingree (1978), showing that the secondary flows generated by eddies provoke convergence towards the centre of the eddy near the bed, and divergence at the surface. Considering that inertial forces predominate over the Coriolis effect, flow convergence near the bed will occur in clockwise and anticlockwise eddies. However, if Coriolis effect is more important than the inertial forces, it is more likely that convergence will occur only where tidal stirring and Earth's rotation are in the same sense (Pingree, 1978), which occurs in anticlockwise eddies on the northern hemisphere.

Pingree used this physical concept to explain sand bank formation in the vicinity of headlands, using as examples, the Isle of Portland (English Channel) and the Lundy Island (Bristol Channel). Apparently, only one sand bank, associated with a residual anti-clockwise eddy, occurs in the vicinity of Portland, while two sand banks exist around Lundy Island.

The significance of the effects in sedimentation processes associated with coastal irregularities was also pointed out by Ferentinos and Collins (1979 and 1980), examining mud and sand deposits associated with tidally-induced eddies, in the Swansea Bay (Wales). These authors, based on Sugimoto (1975), considered that eddies (topographical eddies) formed downstream from headlands and abrupt coastal discontinuities are the result of flow separation, due to the combined effect of adverse pressure gradient and the viscosity against inertia. The development of sedimentary deposits related to topographical eddies depends on the type of sediment available.

Waves also have an important influence on the sedimentary processes acting around headlands, mainly along the associated sand banks. The dispersive and destructional influence of waves, probably, controls the sand bank height, whilst the eddy mechanism reconcentrates the dispersed sediments (Ferentinos and Collins, 1980).

On tidal-dominated continental shelves, sediments, predominantly sands, are swept by strong tidal currents resulting in seabed erosion and bedload transport as longitudinal or transverse bedforms. The works of Stride (1963), Belderson and Stride (1966) and Kenyon and Stride (1970) pointed out the net bedload sediment transport direction on the shelf around the British Isles, based on: the asymmetry of the peak currents on the surface; the elongation of the tidal current ellipse; bedform distribution, considering the asymmetric profile of transverse bedforms with the steeper side showing the direction of transport (sandwaves) and the direction of longitudinal bedforms (sand ribbons); and sediment grain size distribution.

In terms of bedforms and their significance in indicating net sand transport, Belderson et al. (1982) developed a model to predict the development of a suite of bedforms reflecting a decrease in current strength. A general model, disregarding sediment supply, correspond to the following sequence, as the current speed decreases: furrows and gravel waves → sand ribbons → large sand waves → small sand waves → rippled sand sheet and sand patches. Considering a high sand supply model, the development of sand banks are likely to occur.

Sand banks can also be used as an indicator of net sand transport (Kenyon et al., 1981). Linear sand banks are aligned obliquely to the peak current direction and to the net sand transport by about 20°, and usually the crests are rotated anticlockwise in relation to the peak flow direction. Sandwaves are likely to occur on the flanks of the banks with their lee side facing towards the crest, showing a convergent sand transport (Caston, 1972). So, according to Kenyon et al. (1981), sandwaves approaching the bank crest tend to become more parallel to the crest, instead of lying normal to the peak flow direction. It means that the sand transport direction veers to right when approaching the bank crest. Therefore, the asymmetric profile of a sand bank is caused by a flood or ebb peak current asymmetry, and as a consequence, this asymmetric profile is indicating the direction of net sand transport. A fluid-dynamical model for the concepts of Caston (1972) and Kenyon et al. (1981) is provided by Huthnance ($1982_{a,b}$).

Sand accumulation is likely to occur due to bedload convergence or a decrease in the bed shear stress along the transport pathway (Dyer and Huntley, 1999). This investigation discusses a similar pattern of sediment dispersion and deposition around a headland. The characterisation of a complex of sedimentary deposits, instead of just the occurrence of isolated sand banks, brings up a discussion concerning sand transport patterns and bedforms distribution associated with tidal eddies and headlands.

Comparing the suite of bedforms with peak tidal current speeds over the area, a gradient of increasing hydrodynamic intensity is observed along the shelf sand facies, on both sides of the headland: sand sheet, shoals, sandwaves, an unknown intermediate area, and sand bank. Considering that this suite of bedforms could be, regionally, regarded as a single sedimentary deposit, so, as a consequence, a net bedload convergent transport pattern could be described spatially over the shelf, on both sides of the headland (Fig.3).

These patterns could be associated with the transient characteristic of the flow, as it passes the headland. During the tidal cycle, the eddies change in strength, location and limits, which can, probably, control the direction of net sand transport. The importance of transient eddies was pointed out by Signell and Geyer (1991), being more appropriate for applied bedload transport studies than residual circulation.

Nevertheless, wave action must be considered as a factor controlling sand bank evolution (Ferentinos and Collins, 1980), as Lyme Bay occupies one of the most exposed areas along the southern English coastline. Therefore, the great influence of waves on the west side of the headland, appears to be one possible explanation for the no existence of a sand bank on the west side, comparable to the Shambles Bank, on the east side.

The preliminary interpretation is that sedimentary deposits associated with headlands can be more complex than just the presence of isolated sand banks. From the area under investigation, it was observed that a suite of bedforms, including sand shoals and sand banks, occurs on both sides of the headland, being associated with a convergent sand transport pattern.

4. References

Belderson, R.H., and Stride, A.H., 1966. Tidal current fashioning of a basal bed. *Marine Geology*. **4**, 237-257.

Belderson, R.H. Johnson, M.A., Kenyon, N.H., 1982. Bedforms. In: Stride, A.H. (Ed.), Offshore Tidal Sands: Processes and Deposits. Chapman and Hall, London, 27-57.

British Geological Survey, BGS, 1983. Portland sheet. Seabed sediments. 1:250000 series. Keyworth, British Geological Survey.

Caston, V.N.D., 1972. Linear sandbanks in the southern North Sea. *Sedimentology*, **18**, 63-78.

Dyer, K.R. and Huntley, D.A., 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*. **19**, 1285-1330.

Ferentinos, G., and Collins, M.B., 1979. Tidally induced secondary circulation and their associated sedimentation processes. *Journal of the Oceanographical Society of Japan*, **35**, 65-74.

Ferentinos, G., and Collins, M.B. .1980. Effects of shoreline irregularities on a rectilinear tidal current and their significance in sedimentation processes. *Journal of Sedimentary Petrology*, **50**, 4, 1081-1094.

Geyer, W.R., and Signell, R., 1990. Measurements of tidal flow around a Headland with a shipboard acoustic doppler current profiler. *Journal of Geophysical Research*, **95**, (C3)3189-3197.

Huthnance, J.M., 1982a. On one mechanism forming linear sand banks. *Estuar Coastal Mar Sci*, **14**, 79-99.

Huthnance, J.M., 1982b. On the formation of sand banks of finite extent. *Estuar Coastal Mar Sci*, 15,277-299.

Hydrographic Office - UK, 1973. Admiralty Tidal Stream Atlas, Approaches to Portland. NP257.

Kenyon, N.H., and Stride, A.H., 1970. The tide-swept continental shelf sediment between the Shetland Isles and France. *Sedimentology*, **14**,159-173.

Kenyon, N.H., Belderson, R.H., Stride, A.H., Johnson, M.A., 1981. Offshore tidal sand banks as indicators of net sand transport and as potential deposits. *Special Publication International Association of Sedimentology*. **5**, 257-268.

Kenyon, N.H., 1994. Evaluation of seabed character and sediment processes in Weymouth Bay (UK). Tech. Report Amoco (UK), presented to the Dorset County Council. 25p.

Maddock, L., and Pingree, R.D., 1978. Numerical simulation of the Portland tidal eddies. *Estuarine and Coastal Marine Science*, **6**, 353-363.

Nunny, R.S., 1995. Lyme Bay environmental study, Volume 2: The physical environment, sediments. Techn. Report Kerr-McGee Oil (UK), presented to Dorset County Council. 75p.

Pingree, R.D., 1978. The formation of the Shambles and other banks by tidal stirring of the seas. *J Mar Biol Ass U K*. **58,**211-226.

Pingree, R.D. and Maddock, L., 1979. The tidal physics of headland flows and offshore tidal bank formation. *Marine Geology*. **32**, 269-289.

Robinson, I.S., 1983. Tidally induced residual flows. In B. JOHNS (Ed.), *Physical Oceanography of Coastal and Shelf Seas.* (pp. 321-356). Amsterdam-Oxford-New York-Tokyo: Elsevier.

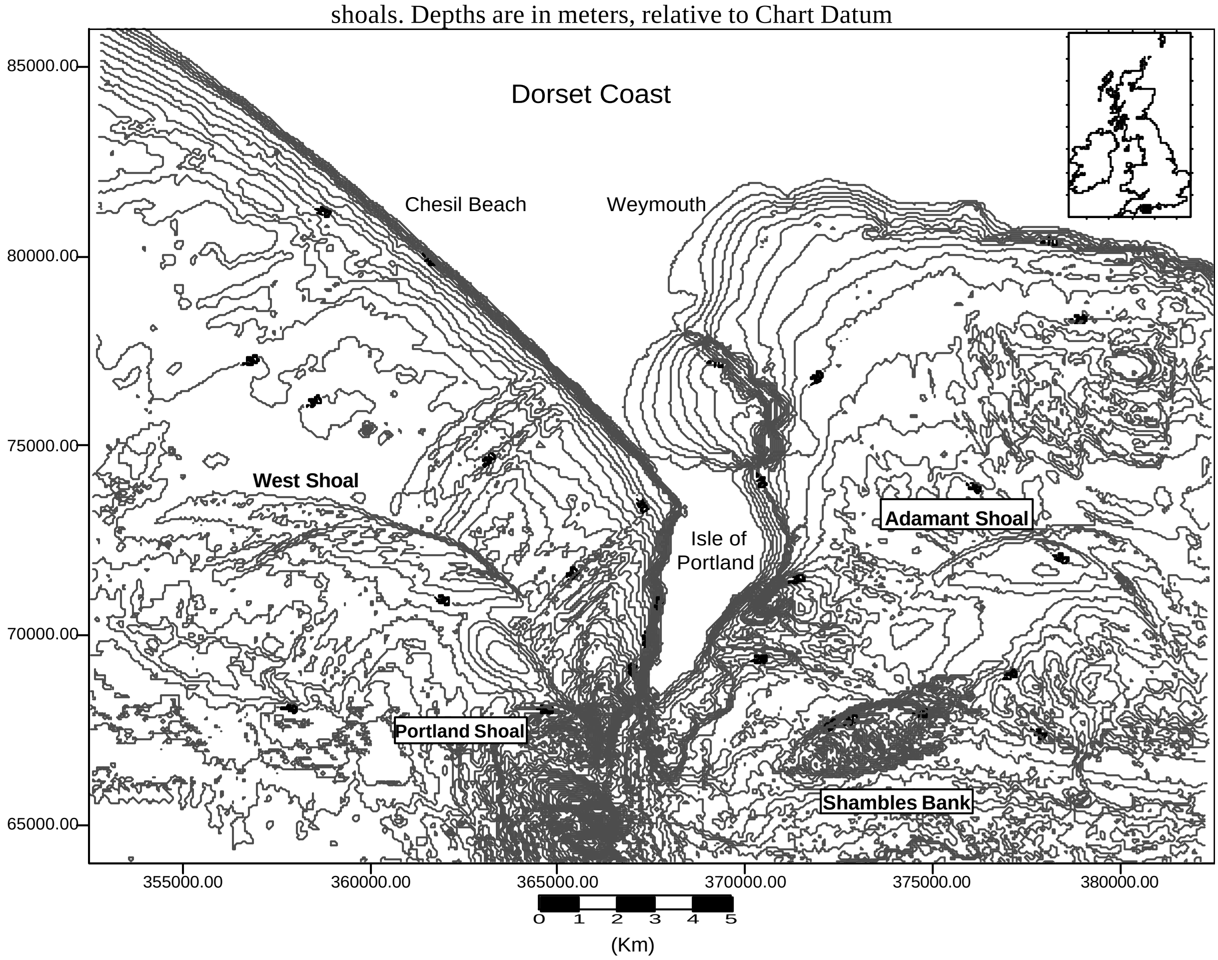
Signell, R., and Geyer, W.R., 1991. Transient eddy formation around headlands. *Journal of Geophysical Research*, **96**, (C2)2561-2575.

Stride, A.H., 1963. Current swept sea floors near the southern half of Great Britain. *Quart. J. Geol. Soc. London*, **119**, 175-199.

Sugimoto, T., 1975. Effect of boundary geometries on tidal currents and tidal mixing. *J. Oceanogr. Soc. Japan*, **31**, 603-628.

Zimmerman, J.T.F., 1980. Vorticity transfer by tidal currents over an irregular topography. *J. Mar. Res*., **38**, 4, 601-630.

Figure 1 – Bathymetric map of the inner shelf around the Isle of Portland, showing the sand bank and sand shoals. Depths are in meters, relative to Chart Datum



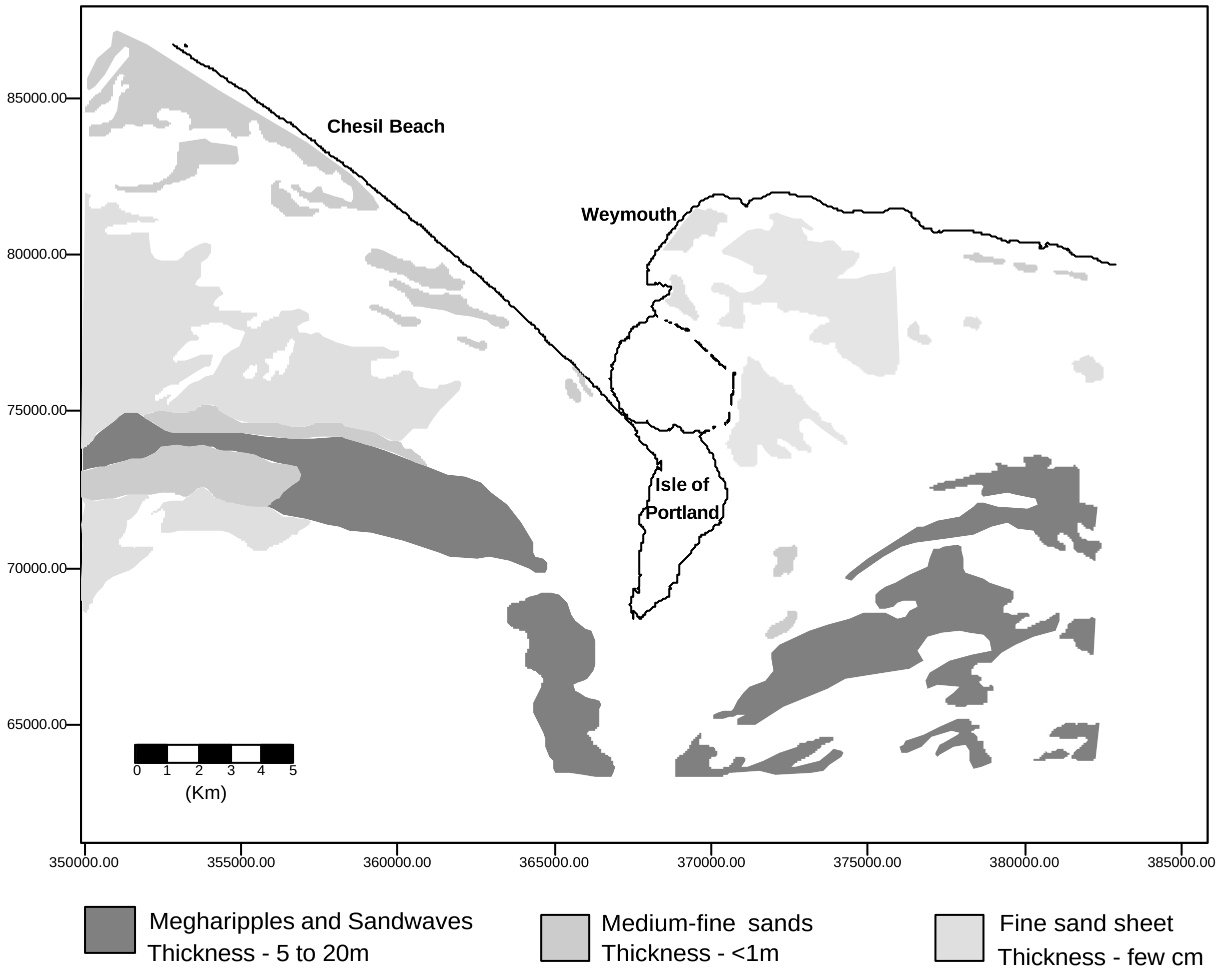


Figure 2 - Patterns of sand distribution and accumulation, showing a symmetrical convergent sand transport towards the headland (Analysis of unpublished side-scan sonar and sample data done for environmental studies and provided to the Dorset County Council, Kenyon, 1994 and Nunny, 1995).

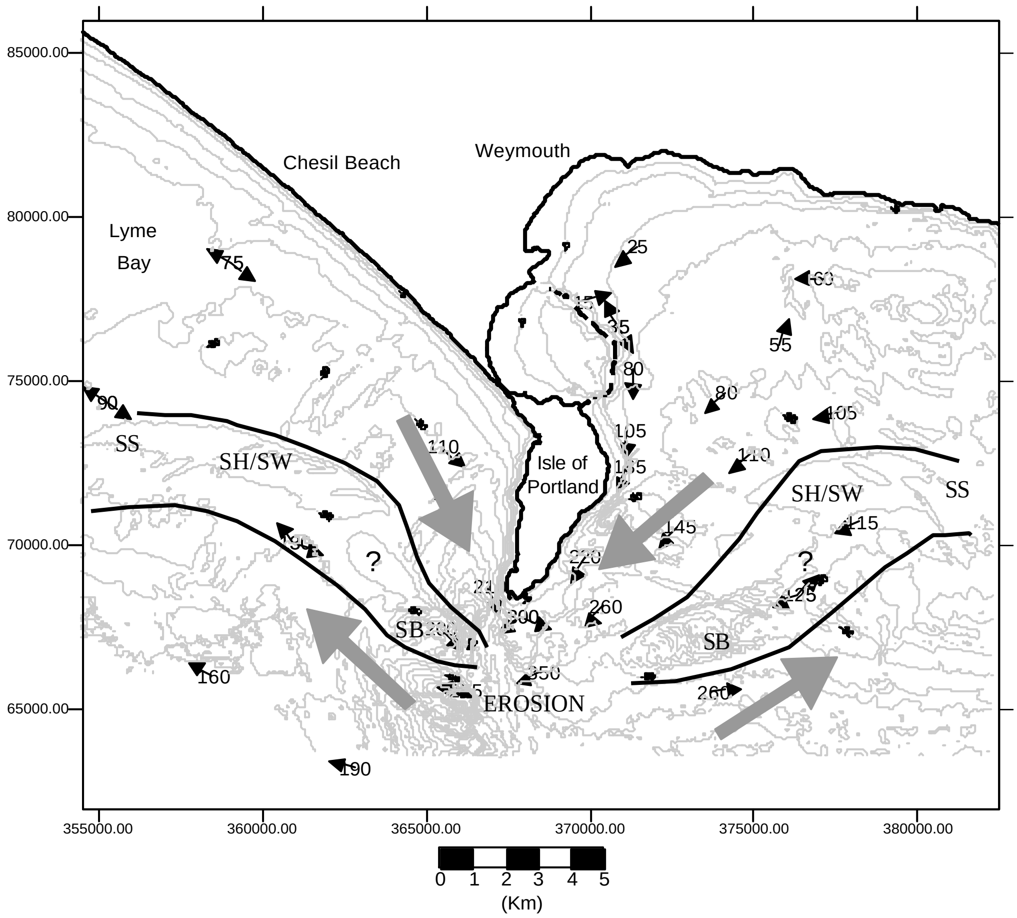


Figure 3 – Distribution of bedforms and the symmetric bedload transport pattern around the Isle of Portland. Key: SS- sand sheet; SH/SW-sand shoal ad sandwave; ?- unknown intermediate area; SB- sand bank, black arrows- direction of peak current asymmetry with speed in cm/s; grey arrows- convergent transport.