Use of swath bathymetry in the investigation of sand dune geometry and migration around a near shore ‘banner’ tidal sandbank

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Abstract: Banner tidal sandbanks in the Bristol Channel have been repeatedly surveyed with a multibeam sonar to study the geometry and migration patterns of superimposed dunes. The data presented in this paper constitute one of the first studies concerned with sediment transport around a banner sandbank (Helwick Sands in the Bristol Channel) using repeated swath-bathymetry. The data reveal that the dunes maintain their shapes over a period of 11 months, and that they migrate in opposite directions on the alternate sides of the bank. Curiously, dunes connect over the crest of the bank despite opposing sediment transport directions on the flanks. Dune height increases with water depth as found in similar environments. We suggest how the morphology of the dunes results from the complex interaction between surface waves and tidal currents that occurs within the proximity of the headland.

Banner sandbanks occur where sediment is abundant, currents are able to induce bedload transport and spatial gradients in the sediment transport flux cause deposition (Dyer & Huntley 1999). Such conditions can be found in some estuarine environments, such as the Bristol Channel (Fig. 1). Popular theories concerning the formation and maintenance of banner banks involve convergence of sediment transport flux induced by residual (averaged over a tidal cycle) current eddies in the pattern of currents eddies originating from coastal irregularities (Pingree 1978; Ferentinos & Collins 1980; Dyer & Huntley 1999). Associated bedforms such as sand dunes are usually well developed on the flanks of active sandbanks. Their orientations in plan view, their asymmetry and geometry in cross-section have been widely used as indicators of the local net sediment transport and hydrodynamic conditions (Harris 1982; Lees 1983; Twichell 1983; Collins et al. 1995; Reynaud et al. 1999; Hennings et al. 2000). Most of the previous studies have focused on the morphology of the dunes rather than on their temporal evolution, and surveys were carried out either with single-beam echosounders or sidescan sonars, with a positioning accuracy of a few tens to hundreds of metres. Recent improvements in positioning at sea and computing methods for processing large amounts of data, however, have facilitated the collection of decimetric accuracy high-resolution bathymetric data with swath sonar (Hare et al. 1995). Furthermore, repeated full bathymetric coverage of sub-tidal sedimentary structures using swath-sonar technology will provide information of their dynamics and three-dimensional characteristics, which are of interest for the understanding of coastal and shelf sedimentary transport.

This paper describes the morphology and dynamical characteristics of sand dunes at the eastern end of the Helwick Sandbank, lying near a headland in the Bristol Channel (Fig. 1). The analysis is based on two sets of swath-bathymetry data collected on 26 September 2001 and 20 August 2002.

The main objective of this paper is to demonstrate the potential for tracking dune migration and dune geometry changes from repeated bathymetric multibeam surveys. This paper is therefore intended to (a) describe the morphological characteristics of the dunes and their spatiotemporal evolution, (b) estimate dune migration rate and from that infer sediment transport flux and (c) relate these data to the work elsewhere of sediment transport around sandbanks and their maintenance. In describing the sand dunes in this paper, we follow the terminology developed by Ashley (1990).

Study area

Helwick Bank is a linear sandbank located off the western end of the Gower Peninsula (Fig. 1).
The bank extends for 13.5 km westward with a bearing of 265°N. It has a maximum width of 2.7 km and a maximum height of 40 m above the surrounding seabed. The area of interest (Fig. 1) encompasses the eastern end of the bank, Port Eynon Bay and the Carboniferous limestone bedrock of Port Eynon Point close to the bank. Its cross-section is asymmetric, with a steep south flank (3.5°) facing south and a gentle north flank (0.6°) facing the coast. Britton (1978) suggested from seismic data acquired over the bank and boreholes in its vicinity that the Helwick Sands reached its present day morphology sometime during the Flandrian transgression (5000 BP). His seismic data show maximum thickness of 40 m of sand overlying a flat surface of Lias bedrock (Neville 1970). Gravel and till deposits, lying between the bedrock and the sand are observed sparsely in the seismic records and have a maximum thickness of 2 m. Britton (1978) suggests that this layer is a relic of piedmont glaciers that extended as far south as the Gower Peninsula during the Devensian glacial period (70 000 BP to 10 000 BP). However, due to the quality of the seismic records, the residual current eddy origin of the development of the bank is still questioned, though considered here being the most probable (HR Wallingford 1997). Hydrodynamic and granulometry data were not collected simultaneously with the bathymetric surveys, but such data have been reported by Postford Duvivier & ABP Mer (2000). That report shows that fine to medium sand composes the surface of the bank ($D_{50}=0.4$ mm). One acoustic Doppler current profiler (ADCP) moored just north of the bank within the Helwick Passage (Fig. 1) recorded maximum ebb (N124°E) and flood (N241°E) which reached 0.84 m s$^{-1}$ and 0.82 m s$^{-1}$, respectively. A second ADCP moored closer to the crest recorded weaker currents with a maximum flood (N295°E) flow reaching 0.35 m s$^{-1}$ and a maximum ebb (N90°E) reaching 0.21 m s$^{-1}$. Prevailing waves approach from the SW (N230°E), according to the ADCP records. The data show a 4.25 m maximum significant height (one third of the highest waves) and 9.63 s period.

**Fig. 1.** Physiographic map of the Helwick Sandbank and Port Eynon Bay. Depth contours are displayed every 3 m, with 10 and 25 m in bold (depths are relative to Chart Datum). The coordinates are converted to the Universal Transverse Mercator system zone 30 (projected using the WGS84 ellipsoid), so that distances be measured in metres directly from the maps. Inset: The Bristol Channel and location of Helwick Sands. Location of two other banner sandbanks (Scarweather and Nash) is displayed.
Fig. 2. Grey-shaded maps of bathymetric data collected with a Reson Seabat 8101 multibeam sonar along the southwest coast of the Gower Peninsula. The gridded data have 1 m spatial resolution. The data are illuminated from the NW. Dashed lines represent the crest of the bank. (a) Overview of the data encompassing the eastern Helwick Sands, its connection with the bedrock near Port Eynon Point, the subtidal Port Eynon Bay and a nearshore region west of Port Eynon Point. Continuous lines represent water depths contoured every 5 m. Inset: example of small dunes superimposed on the stoss side of medium ones. (b) and (c) The area of repeated coverage (26 September 2001 and 20 August 2002 respectively). The 2001 dataset is noisier due to an erroneous setting of the heave filter, but positions still have decimetre precision. Note the similarity in plan-form shapes of the dunes between the two surveys.
The present-day morphology of the bank is likely a result of the action of both the tidal currents and surface waves, as has been inferred for numerous other shallow banks (Huthnance 1982a; Pattiarchi & Collins 1987; Houthuys et al. 1994; Collins et al. 1995; Reynaud et al. 1999; Mallet et al. 2000).

Repeated multibeam sonar surveys

The data presented in this paper are based on two bathymetric surveys over the same area carried out with a Reson Seabat 8101 multibeam sonar. The system consists of 101 echo-sounding beams, each with an aperture of 1.5° by 1.5°, which ensonify the seabed across a 150° fan. The location and water depth of each footprint within the swath are geo-referenced using the position and motion data of the boat. That are collected simultaneously with an Applanix POS/MV220 motion sensor. Processing of the data involves the manual editing of erroneous depth measurements, merging the data from the different sensors with corrections related to the tidal height and the celerity of the acoustic pulse in the water column.

The 2001 survey covered mainly the southern flank, but also a small part of the northern flank (Fig. 2b). The 2002 survey covered the eastern end of Helwick bank, on both flanks and adjacent coastal areas (Fig. 2a and c).

During both surveys, data were acquired in relatively calm seas. In 2001, tidal heights were collected at the Mumbles UK national tide gauge, whereas in 2002, they were also collected simultaneously on an adjacent beach located less than 5 km from the surveyed area. The comparison of the two tidal signals allowed the determination of a tidal range multiplier and a phase offset, which have been applied to the 2001 Mumbles tide gauge data to correct the 2001 bathymetric dataset.

All depths in this paper are given relative to Chart Datum. The surveys extend from 4 m at the crest of the bank to 40 m at the base of the southern flank. The crest of the bank connects to the bedrock sub-tidal extension of Port Eynon Point through a depression where the water depth ranges from 8 m to 10 m (Fig. 2).

Mapping of dunes

Small and medium dunes are superimposed on both flanks and the crest of the bank. Small dunes have been described as transient or highly dynamic morphological features, which can be obliterated by meteorological events such as storms (Houthuys et al. 1994). They are present on the stoss sides of several bigger dunes, mostly located on the base of each flank of the bank (see inset to Fig. 2a). The direction of their crests, on the northern flank, is sub-parallel to the crests of the medium dunes that they cover. At the base of the southern flank they are orientated c. 30° oblique to the dune crest. Bennett & Best (1995) suggest that flow separation occurring at the crest of large dunes induce a zone of detachment, in which turbulences affect the mode of sediment transport and may lead to the formation of smaller scale dunes.

Although, medium and large dunes can occasionally reverse within a tidal cycle (Hawkins & Sebbage 1972; Berné 1993; Lanckneus & De Moor 1995) or more especially because of atmospheric events (Le Bot & Trentesaux 2004), they are generally recognized as persistent features over many tidal cycles (Lanckneus & De Moor 1991; McCave 1971). Therefore, their morphology has been widely used as an indicator of the time-averaged direction of sediment transport (Perillo & Ludwick 1984; Smith 1988; Lobo et al. 2000; Berné et al. 1994; Van Lanker & Jacobs 2000).

The artificial illumination on Figure 2 (from the NW) highlights the dune crests and their western slopes facing the illumination. The strike of the dune crest lines is roughly transverse to the axis of the sandbank except towards the crest of the bank (dashed line on Fig. 2) where they curve at an oblique direction of N50°E. They are generally laterally continuous from one flank of the bank to the other. This configuration leads to a high degree of sinuosity, with a maximum inflexion coinciding with the crest of the bank. Bifurcation of dune crests was observed occasionally, such as along the southern base of the bank, below 35 m depth and, to a lesser extent, over the crest of the bank (in the area of maximum inflexion of the dune crestlines). A similar dune plan-form geometry was observed in the 2001 and 2002 surveys (Fig. 2b and c respectively), confirming that dune geometries are stable over a period of 11 months.

Fig. 3. Geometrical characteristics of dunes in the area of repeated surveys. Dune height, spacing and asymmetry have been measured from profiles run roughly parallel to the sandbank crest. (a) 2002 survey dune height measured from crests to the average of the adjacent troughs (m). (b) Dune spacing measured from two consecutive troughs (m). (c) Sense and magnitude of the asymmetry of the medium sized dunes (ratio of the horizontal length of the lee side to the length of the stoss side).
Sand-dune morphology has generally been summarized using their height, spacing and asymmetry. Bathymetric cross-sections were taken parallel to the crest of the bank to measure these parameters from. Figure 3a shows a map of the heights \(H\), derived from the vertical distance between the dune crest and the average of the depths of the adjacent troughs. Dunes taller than 2 m are found on the southern flank, with maximum values around 4 m at the base of the bank. Slightly smaller dunes within the 2–3 m range are located on the northern flank of the bank, near the headland. At the crest of the bank, the dune heights tend to reduce to 1 m, especially where the plan-view sinuosity inflexion occurs. The smallest dunes in the studied area can be seen north of the 15 m contour (northern limit of the data in Fig. 3a), where they reach heights of 0.6 m to 1 m and at the far southeastern corner of the studied area where their heights are around 1 m.

Dune Spacing or horizontal length \(L\) was measured as the horizontal distance between two consecutive troughs and is shown in Figure 3b. Smaller dune spacing \((c. \, 60 \, m)\) than the 110 m average occurs at the base of the southern flank, where most of the bifurcation occurs. The dune spacing increases \((190–200 \, m)\) towards the crest of the bank. Finally, on the northern side of the bank, as it approaches the headland, dune crests are spaced by 40–80 m.

As mentioned earlier, the asymmetry of the dunes is a good indicator of the direction of the sediment transport. Various definition of the symmetry index can be found in the literature. Allen (1980) defines it as the ratio of the horizontal lengths of the lee and stoss slopes. These were measured as the distance between the crest of the dune and the corresponding trough along the profiles and results are shown in Figure 3c. Symmetric dunes are present in three areas: (1) at the crest of the bank, (2) where the bank lies closest to the headland and (3) at the westerly side of the southern flank of the bank (Fig. 3c), where the dune crests are linear and perpendicular to water depth contours. Dunes with easterly facing lee sides dominate the northern flank of the bank. Their lee and stoss slopes are typically \(c. \, 2.2^\circ\) and \(c. \, 0.7^\circ\), respectively. The dunes are symmetric over the crest of the bank, with slopes of \(c. \, 1^\circ\). Further south, the dunes are asymmetric with lee slopes of \(1.5^\circ\) to \(2^\circ\) facing west and stoss slopes of \(0.5^\circ\) to \(1^\circ\). At the southern base of the flank, the lee sides of the dunes dip at angles of between \(4^\circ\) and \(7^\circ\) compared to angles of \(2^\circ\) to \(3^\circ\) for the stoss side. From the above, the sediment transport is towards the east on the north side of the bank and towards the west on the south side, while there is no resolvable transport direction over the crest.

Geometrical features of dunes reflect the current strength, the wave regime and characteristics of the sediment (Flemming 2000). A detailed study of the dune heights \((H)\), dune crest water depth \((z)\) and dune spacing \((L)\) was therefore carried out to relate the characteristics of the sand dunes to the conditions of sediment transport as found in other studies.

The size (height and spacing) of the dunes show some variation along crestlines (Fig. 3a and b). To suppress this dispersion of the data, we only use the maximum height of the dune \((H_{\text{max}})\) and its corresponding spacing and water depth to plot Figure 4. The properties of the dunes were measured in three depths region based on the above observations: below 25 m, corresponding to the foot of the bank, between 25 m and 15 m, corresponding to the flanks of the bank and from 15 m to the crest of the bank. Correlation between the shape of the dune and the water depth can be expected as water depth can affect the size of the turbulent boundary layer and limit the development of wakes and turbulences on the lee side of the dunes (McLean 1989). Figure 4a clearly shows that sand dune height increases with increasing water depth. A linear trend fitted to the data by least-squares indicates that the relation \(H/z\) is 0.11, which is comparable with the widely accepted relation of Yalin (1992): \(H/z = 0.167\) for dunes submitted to a unidirectional flow. Figure 4b, displaying the relation between the dune spacing and the water depth, shows no correlation, as spacing varies weakly. Flemming (2000) defines steepness as the ratio of dune height over its spacing. Figure 4c shows the steepness of the dunes for each of the depths groups. Flemming found a relation \(H_{\text{max}} = 0.0667L^{0.8}\) by power regression on 1491 data, with a coefficient of correlation, \(R = 0.98\), which holds for dunes that have reached their equilibrium. For each of the dune groups, power regressions were fitted through the data. At the foot of the bank (below 25 m), dunes are steeper than those analysed by Flemming, while above 25 m the dunes tend to flatten (Fig. 4c). The tendency to flatten could arise from one or more effects: (1) increasing resuspension and bedload movements by surface waves that are likely to

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Fig. 4. Relationships between dune geometrical parameters. Data used to plot these graphs correspond to the maximum height of each dune in the corresponding water-depth range. Dune height \((a)\) and hence dune flatness \((c)\) are depth dependant. Wave-induced flattening of dune crests are speculated to be important at the crest of the bank.
a) Below 25m

b) Between 25m and 15m

\[ H = 0.1122z + 0.0807 \]

\[ H = 0.7551L^{0.2445} \]

\[ H = 1.4145L^{0.0236} \]

\[ Yalin (1977) \]

\[ Yalin (1964) \]

\[ \Delta \text{ Between 15m and crest of the bank} \]

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intensify towards shallow water and with proximity of the surface; (2) the tidal current intensifying as it is concentrated through a narrower depth extent as proposed for flattening of sand banks at larger scale (Huthnance 1982b); and (3) the effect of shallow water in reducing the vigour of lee-side eddies (Kostaschuk 2000).

Dune migration

Langhorne (1982) noticed that the shapes of dune crests can be strongly influenced by reversing tidal currents. Berné (1993) showed that rounded crests, or ‘cat-back’ profiles, can form in response to varied tidal asymmetry over neap-spring cycles and strong currents. Cat-back profiles are common on the southern flank indicating the predominance of such strong and directionally varying tidal asymmetry. Therefore, difficulties arise in mapping the transient crests of such cat-back dunes, and hence changes in the location of the dune crests can not be considered to be the best measurement for resolving their long-term migration. We therefore developed an alternative method based on isolating and displaying the ‘mobile dune layer’ along with cross-sections in order to identify and quantify dune migration. A drawing defining the mobile sand layer \( h(x,t) \) is presented in the inset to Figure 5. This layer represents the thickness of sand continually masked by the dunes and was found to highlight their plan-view shapes quite well.

Comparison of vertical profiles, such as those in Figure 6, along with Figure 5 enabled us to track dunes from one survey to the other. confidently tracked dunes are referred as A to M on the 2001 survey along the southern flank and 1 to 15 along the northern flank. Apostrophes are applied for the 2002 dunes. Note similarities in plan-form shapes of dunes defined by the \( h=0.5 \text{ m} \) contour, it is clearly disconnected from dunes in the north. Dune 7 has been migrating eastward, and has connected with dune C’ temporarily in the period between the two surveys, but was disconnected from dune C’ by the time of the 2002 survey. Dune 8’ was then laterally connected with dune C’.

Merging can also be observed. For example, dune H was split in two parts and barely connected with dune 10 on the 2001 survey (Fig. 5a). In the time between the surveys, the southern part of dune H migrated faster than the northern part. In 2002, the northern part of dune H’ has show a simple migration during the 11 month-period separating both surveys, with a mean of 22 m (10 m standard deviation) along the southern profile, compared with 34 m (13 m standard deviation) on the northern profile. The respective annual migration rate 24 m a\(^{-1}\) and 37 m a\(^{-1}\) are relatively slow migrations compared with the values reported by in Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (2003) review, which range from 7 to 220 m a\(^{-1}\). Among 11 dunes, 8 show a volume change of less than 25%. The geometrical similarity between the dunes in plan-form and cross-section between the two surveys (Figs 5 and 6) is interpreted as the product of predominantly bedload transport leading to simple dune migration (Van den Berg 1987).

The tracked dunes reveal migrations with the same directions expected from the dune asymmetry (Figs 3c and 5). Along the southern side of Figure 5 dunes are migrating westward, whereas along the northern side dunes are moving eastward. The boundary between the zones of opposite migration coincides with the cresteine of the bank (Fig. 2, and dotted line on Fig. 5).

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merged with dune 12’ to form a single laterally continuous dune from one side of the bank to the other. In some cases, dunes have also amalgamated. For example, dune 6 presents a ‘X’ planform on the 2001 survey. In 2002, both southern legs of the ‘X’ shape are amalgamated and form dune 6’ which is laterally connected to dune B’.

An unusual feature of the dunes in Figure 5 is that many show an across-bank continuity (over the crest of the bank) despite migrating in opposite directions along the flanks. Opposite migration on the flanks of sand banks has been widely reported (Caston 1981; Reynaud et al. 1999; Mallet et al. 2000; Bastos et al. 2002) but the continuity of the dunes over the crest of a bank has been rarely described and not as far as we are aware ever properly explained. The observations suggest that a three-step mechanism is involved. First, dune crests deform or bend, due to the gradient of the clockwise circular net residual current along the sandbank inferred by numerical modelling (HR Wallingford 1997). Second, they split or break laterally, and third rejoin with another crest. We speculate that the latter may be encouraged by along-dune crest sediment transport driven by surface waves.

Table 1. Morphologic evolution and migration of the dunes reported in Figure 5

<table>
<thead>
<tr>
<th>Dune (as referenced on Fig. 5)</th>
<th>Cross-sectional area (m²)</th>
<th>Cross-sectional area changes (%)</th>
<th>Migration (m)</th>
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<td>26/09/2001</td>
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Fig. 6. Segments of collocated profiles (a) on the northern flank and (b) along the southern flank. In each figure, the data from 2001 are shown above the 2002. Interpreted similar dunes both in plan-form and cross-section are connected by lines between crests.
because the predominant wave direction is from the SW here (Postford Duvivier & ABP Mer 2000), parallel to the crestal dunes. This last mechanism was suggested by McCave & Langhorne (1982) for bank-crossing small dunes, at the end of the Haisborough Sand in the southern North Sea. Our ongoing research is attempting to resolve whether sand fluxes due to surface waves recorded here are sufficient to cause this evolution.

The sand dune asymmetry and migration therefore indicate a circular (clockwise) sediment transport around the bank, as described in the literature for other types of sandbanks. As predicted by Pingree & Maddock (1979), gradients in the residual tidal currents arise from the interaction of the currents with the headland and the topography of the bank itself. Huthnance (1982b) also predicted a deflection of the flow over the crest of sand banks caused by the effect of friction. These mechanisms are partly responsible for the oblique dune orientation over the crest of the bank. The determination of tidally- or wave-driven flux of sediments at the crest of the bank is still under investigation.

**Conclusion**

Two multibeam surveys over the eastern end of Helwick Bank, as it approaches Port Eynon Point headland, have been used to assess the characteristics of sediment transport. The sense of sand dune asymmetries indicates the directions of the sediment transport. The dunes are also correlated by geometrical similarity both in plane-form and in cross-section between the two surveys. The tracked dunes suggest that they migrate relatively simply without major change in shape, which is characteristic of bedload transport.

Both asymmetry and migration of dunes indicate opposing transport directions on the two sides of the bank, suggesting a clockwise sand circulation. Some dune crests connect continuously over the crest of the bank. This phenomenon remains unexplained, but we speculate that wave-induced sediment transport could play an important role. It has also been shown that dune height increases with increasing water depth, whereas dune spacing does not, a result of flattening of the dunes over the crest of the bank. Dune flattening would also be consistent with stronger wave-driven transport at the crest of the bank.

This study illustrates how multiple swath-bathymetric surveys provide quantitative information of both the morphology and the evolution of sand dunes. Frequent usage of this technique will provide more *in-situ* information, which will be highly valuable in the development of our understanding of sedimentary processes affecting coastal and shelf areas.

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