Sand wave morphology and development in the Outer Bristol Channel (OBel) Sands

J.W.C. James
British Geological Survey, Nicker Hill, Keyworth, Nottingham, NG12 5GG, UK.

ABSTRACT: The Outer Bristol Channel (Obel) Sands is a sand wave field which covers an area of at least 1000 km^2, with a high density of sand waves in the north and numerous isolated sand waves to the south. It is an area of west flowing ebb current dominance. The principal sand waves (~5 – 20 m high) are generally asymmetrical with west facing lee slopes. Although there is seismic evidence of growth in height and volume of the large asymmetric sand waves and westward migration over time, in present day conditions the structure and position of the large sand waves is being maintained by the opposing tidal currents suggesting that the large sand waves are not moving westward under the influence of ebb tidal dominance but are in a state of *in situ* equilibrium with little or no new sediment being introduced into the system from the east.

1 INTRODUCTION

The Outer Bristol Channel Marine Habitat Study (Fig. 1) (James et al. 2004, Mackie et al. 2006) was undertaken to collect and provide data and interpretations on the current physical state of the area's sea bed environment in terms of its biology, sediments, geology and morphology, how these elements interact and relate to each other and the natural processes which influence and impact the sea bed environment. The area of study covered approximately 2400 km2 of the sea bed from Carmarthen Bay in the north to Lundy Island 60 km to the south and included the sand wave field comprising the Outer Bristol Channel (OBel) Sands. The study was led jointly by the British Geological Survey (BGS) and the National Museum of Wales (NMW).

1.1 *Regional setting*

The Outer Bristol Channel lies to the western end of the Bristol Channel. It merges into the Celtic Sea, south-east of Milford Haven, and from here the Bristol Channel extends eastwards for around 160 km to Chepstow in the Severn Estuary. From west to east it gradually diminishes in width from over 70 km south of the Pembrokeshire coast to about 8 km at Avonmouth, Bristol.

The central axial floor of the Bristol Channel gradually deepens from east to west. The Inner Bristol Channel has wide areas with depths of 10 to 30 m. These deeper waters become more extensive in the Central Bristol Channel and further west reach 50 to over 60 m in the Outer Bristol Channel.

1.2 *Geology and sea bed sediments*

The Bristol Channel has a central floor which comprises a submarine valley system, which extends up into the Severn Estuary. This system was incised during the late-Tertiary – early Quaternary and modified to some extent during subsequent Quaternary glaciations and inter-glaciations The form and morphology of the present-day sea bed includes elements which are directly related to the erosional and depositional events associated with the formation of the submarine valley, for example, rock platforms, and glacial deposits such as tills. However, the sea bed also includes morphological features which are related to the submergence of the Bristol Channel by rising seas after the last Glaciation, and the deposition and re-working of sediment, some of which may have been of fluvial and glacial origin, during and after this marine transgression. A particularly significant element is the fashioning of sea bed sediments into major large scale bedforms such as sand banks, and relatively smaller bedforms like sand waves and sand ribbons by marine processes.

The sediments lying at the sea bed in the Bristol Channel and Severn Estuary include a variety of lithologies from mud to gravel but there are also widespread and significant areas of rock exposed at the sea bed. In deeper water in the Outer Bristol Channel there is an extensive sand wave field which is the area covered by this study.

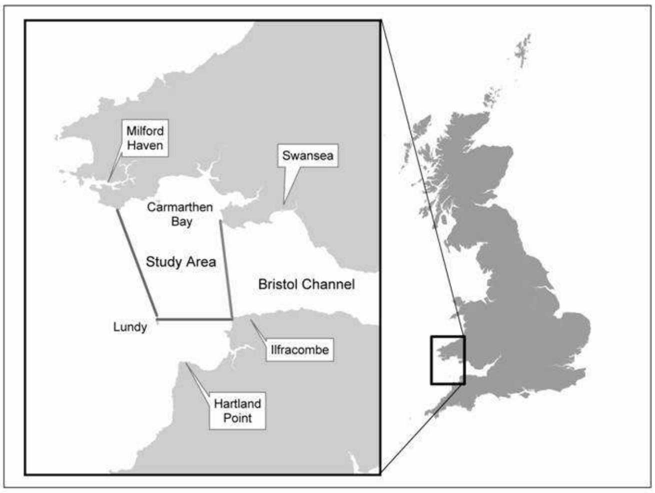

Figure 1. Location of study area

1.3 *Hydrodynamics*

The Bristol Channel is noted for its significant tidal range, one of the largest recorded in the world. At Avonmouth, the range of the spring tide is greater than 12 m. Further west in the Outer Bristol Channel the mean springs range is around 7 m. Allied to these high tidal ranges are strong rectilinear currents which are predominantly aligned along the central axis of the channel. In the Outer Bristol Channel these can reach depth averaged velocities of $1.2\ m\ s^{-1}$.

Tides are semi-diurnal. During each cycle between ebb and flood, tidal currents can move water large distances, between 10 and 22 km up and down the Channel (Shaw, 1980). However, although the gross distances are large, the long oscillation of the tides means that net movement of water is relatively small (IMER, 1974).

1.4 *1.4 Sedimentation processes*

Mapping of the sea bed using geophysical records including echo sounder and side scan sonar in the 1970’s and 80’s enabled the interpretation of bedforms such as sand waves, pinpointed the location of rock outcrops and enhanced our knowledge of the morphology of sand banks. This gave primary physical data for sediment transport modelling. Belderson & Stride (1966) used this type of sea bed geophysical data to provide evidence of bedform asymmetry as an indication of net sediment transport direction. They postulated a sediment bedload parting in the Inner Bristol Channel with ebb dominated net sediment transport to the west of the bedload parting down the channel. On the east side of the parting, net sediment transport is flood dominated into the Severn Estuary. The physical evidence for a bedload parting in this area fits well with the results of modelling (Uncles, 1982; Pingree & Griffiths, 1979) with tidal residuals and asymmetry indicating an ebb dominant system to the west of this parting zone and a flood dominant system to the east. The bedload parting zone is co-incident with the area of highest bed sheer stress.

Harris & Collins (1985) also interpreted side scan sonar records in the Bristol Channel. From the evidence they gathered, including bedform asymmetry, they proposed a ‘mutually evasive’ sediment transport model for the Bristol Channel with an ebb dominated system down the central axis of the channel and a narrow flood dominated system adjacent to the northern and southern coastlines indicating net sediment transport eastwards up the channel margins. The two models have stimulated further debate (Stride & Belderson, 1990; Harris & Collins, 1991). There are elements that are common to both models and they are not exclusive of each other, the principal difference being sediment transport pathways in the marginal coastal areas. However, in all models the Outer Bristol Channel Sands are within an ebb dominant system.

Modern input of sediment into the Bristol Channel is primarily fine-grained muddy sediment from rivers and minor contributions from coastal erosion. The rivers with the greatest input are the Wye, Avon and Severn, which discharge into the Severn Estuary. Some exchange of sediment has been postulated between the Celtic Sea and the Bristol Channel; however this is only likely along the coastal margin and would only be a minor contribution. There appears to be no major substantial source of sand feeding into the modern Bristol Channel system.

2 SURVEY METHODS

Following an initial interpretation of the geology of the area a survey strategy was devised to provide multibeam echo sounder (Reson 8101) and multipulse (Edgetech MP-X) and multibeam (Klein 5000) digital sidescan data married to coverage of the study area at a regional scale. The strategy was to survey eleven kilometre wide corridors with complete multibeam and sidescan coverage (Fig. 2). The corridors are 25 to 40 km long with centre lines at approximately 5 km spacing. They are aligned roughly parallel to the predominant tidal stream and at right angles to the regional trend of the sand wave crest lines in the OBel Sands. A boomer sub-bottom reflection seismic line was run down the centre of nine corridors. A programme of sediment grab sampling and sea bed video was also conducted.

3 OUTER BRISTOL CHANNEL (OBEL) SANDS

The Outer Bristol Channel (Obel) Sands is a sand wave field which stretches westward for over 40 km along the southern margin of Carmarthen Bay (Fig. 2). Although it narrows to the south it extends for

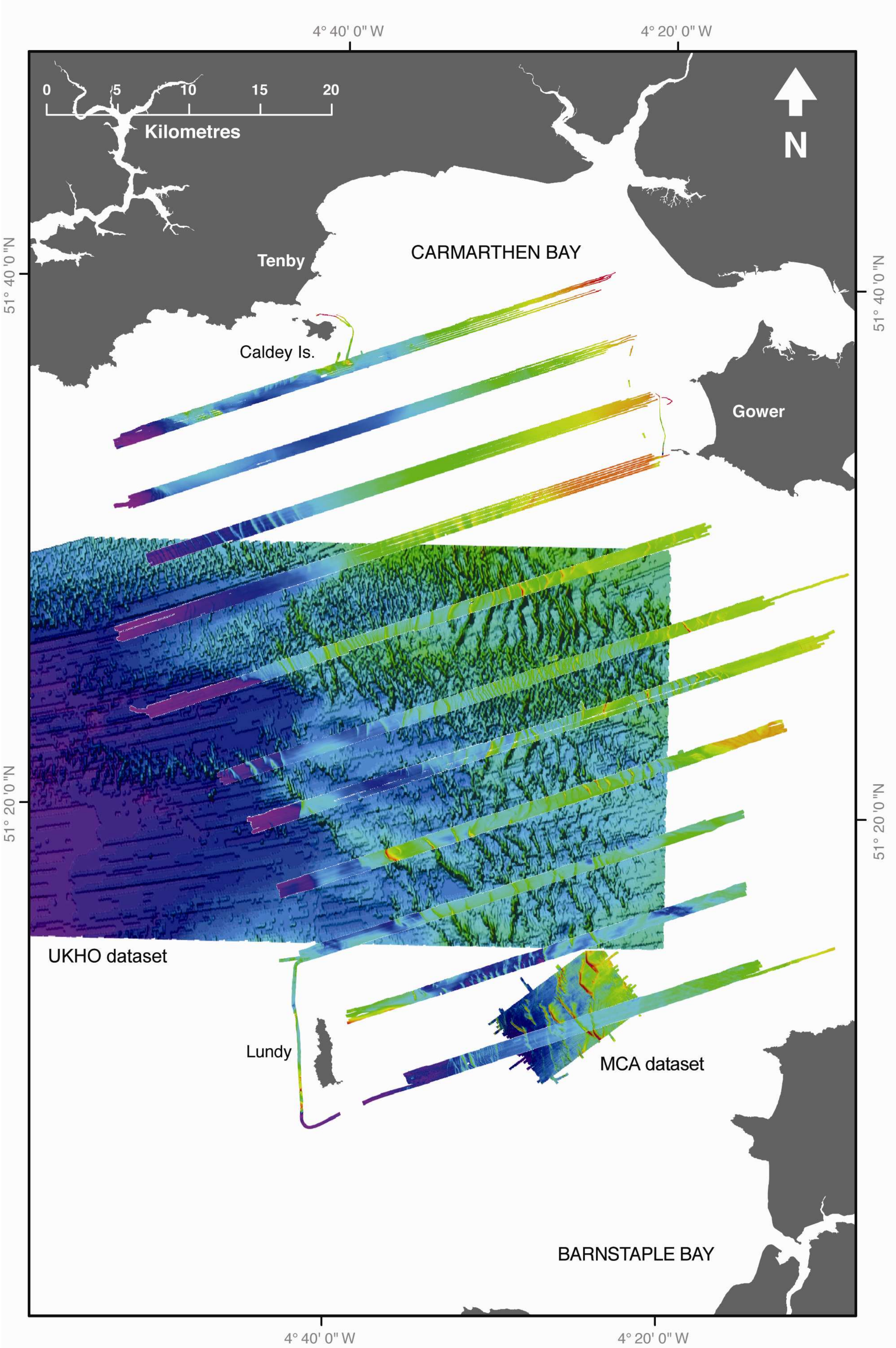

Figure 2. The OBel Sands imaged with UK Hydrographic Office (UKHO) single beam, and Maritime and Coastguard Agency and BGS multibeam data. (UKHO data derived in part from material obtained from the UKHO with the permission of the Controller of Her Majesty's Stationery Office and UKHO. © British Crown & SeaZone Solutions Ltd. 2004. All rights reserved. Data Licence No. 112005.006).

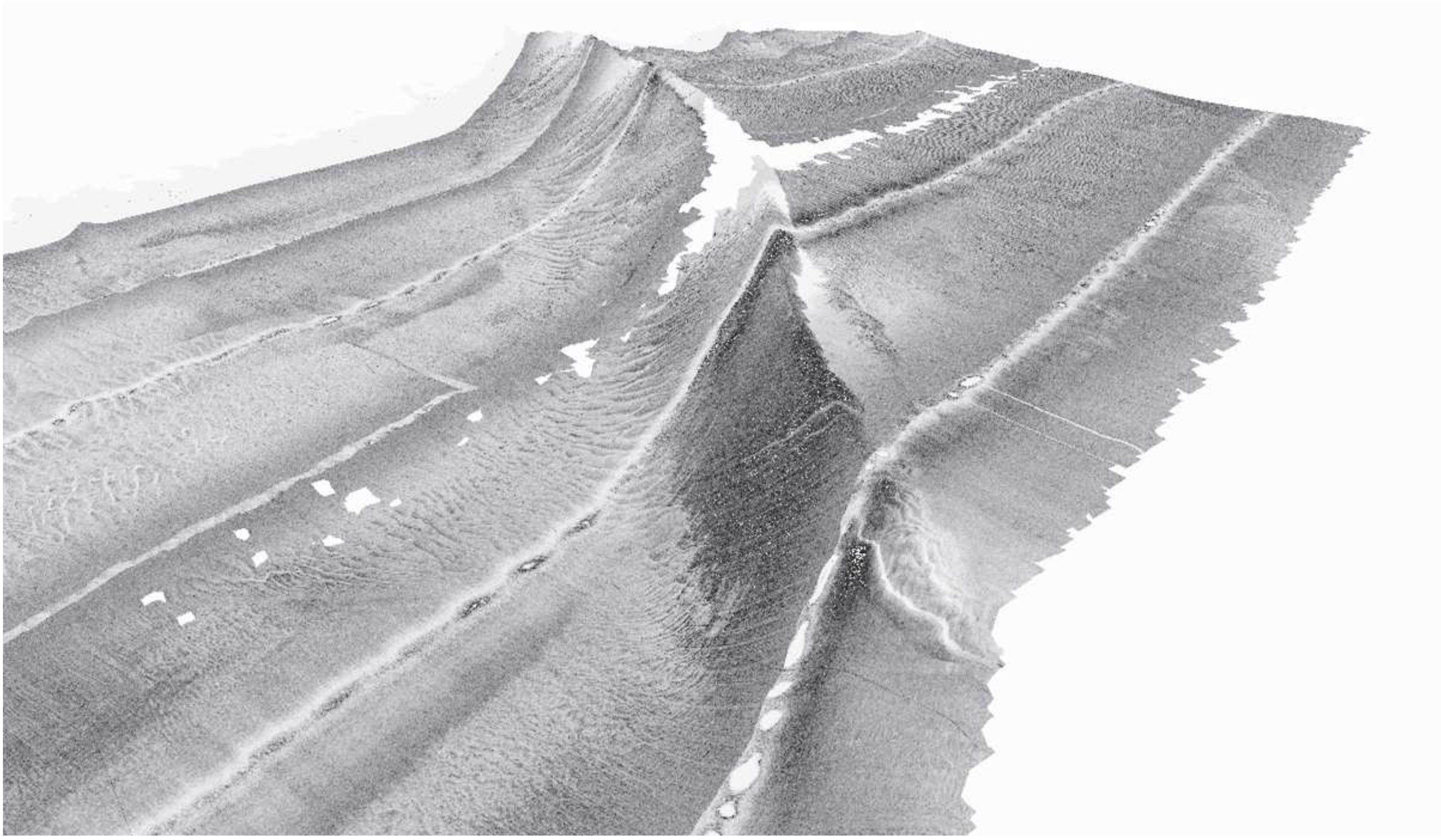

Figure 3. 3D image of 18 m high sand wave with sidescan mosaic draped on multibeam surface. Survey corridor ~900 m wide. ©NERC/NMW

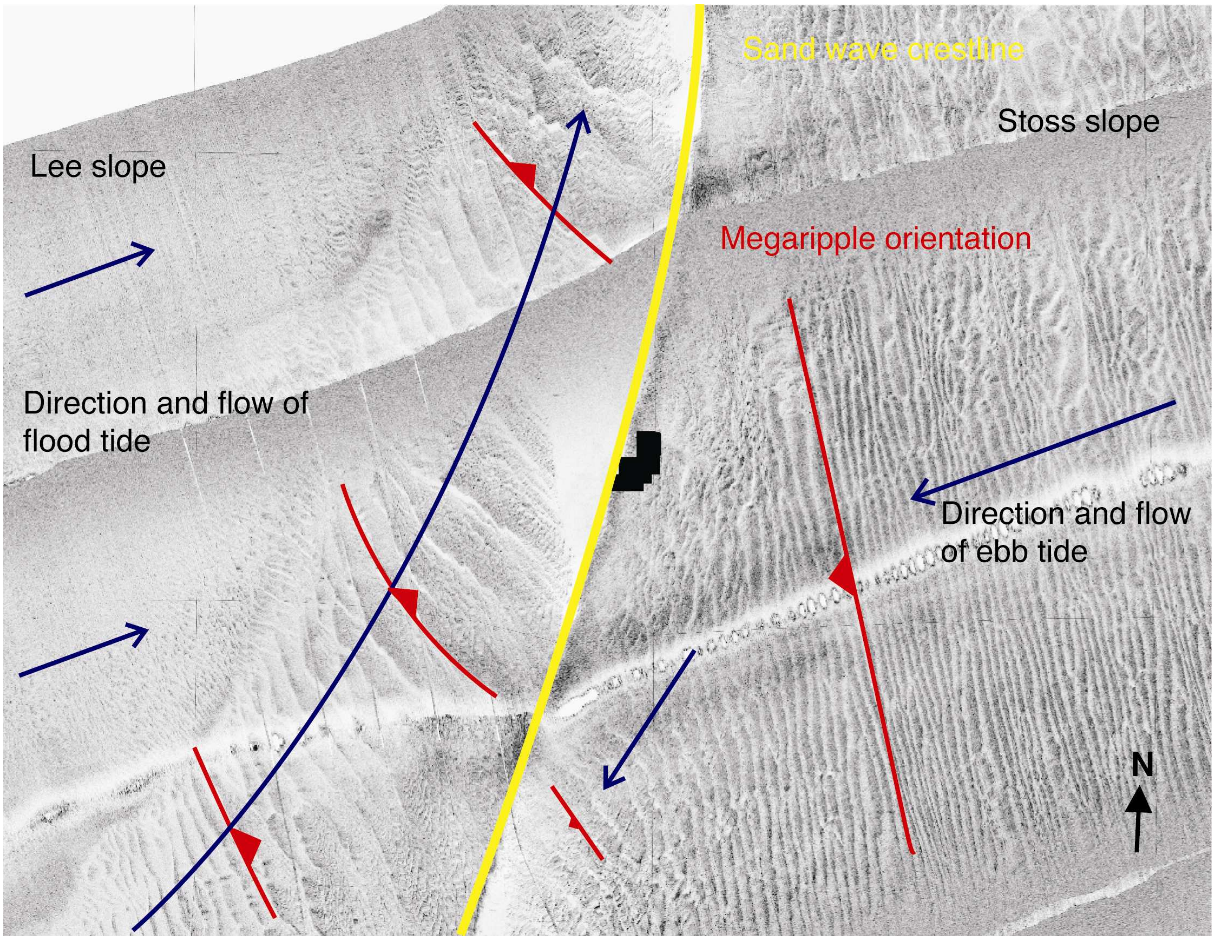

Figure 4. Sidescan plan view of 18 m high sand wave in Figure 3 showing variation in megaripple orientation on lee and stoss slopes. Image is ~450 m E-W. . ©NERC/NMW

over 37 km to the southern boundary of the study area, where it is around 12 km wide. In total it covers an area of at least 1000 km^2. The OBel Sands have been divided into north and south sectors.

The North Outer Bristol Channel Sands (NOBel Sands) are characterised by a high density of large and small sand waves on a predominantly sandy sea bed. From east to west it extends for over 40 km and at its maximum is about 12 km wide. The ambient sea bed declines to the west from a depth of about 37 m at the eastern margin of the NOBel Sands to below 60 m.

The South Outer Bristol Channel Sands (SOBel Sands) are characterised by numerous isolated sand waves on a dominantly coarse substrate of gravelly sands to gravels. Sand wave frequency decreases to the south, with a relatively flat sea bed at around 45 m at its southern margin.

3.1 *Sand wave morphology and development*

The maximum sand wave height observed in the NOBel Sands is 19 m, though more commonly heights are of 12-14 m. The crests of the sand waves in the eastern and central part of NOBel Sands lie in water depths between 25 m and 40 m, whereas those further to the west have crests in water depths of 40 m to 60 m. The distance between the individual waves varies on average from 1000 m to 1500 m, though the lower and upper ranges observed are 600 m to 3000 m. The sand waves are laterally extensive and continuous, with crest lengths ranging from 1 km to 7 km long.

The sand wave crests are oriented with a regular sinuosity aligned on two principal trends NNW (330°/340°) to SSE (150°/160°) and NNE (10°/20°) to SSW (190°/200°). The former is the dominant trend. Both these trends may be a product of the slight variation seen in the direction of the principal ebb and flood currents. Two surface current tidal stream roses from UKHO Charts in the centre of the Channel and on the west and east side of the Outer Bristol Channel Sands are not wholly rectilinear. The eastern rose is more elliptical but with a dominant vector for the flood current around 65° to 95° at a speed of 1.2 m s^{-1} and the ebb current around 250° at 1.4 m s^{-1}. The western rose indicates a decrease in current speed westward across the OBel Sands although the rose is more linear with peak flood direction around 72° to 76° at 0.8 m s^{-1} and the ebb current around 262° to 267° at 0.9 m s^{-1}. The two principal sand wave crest trends are transverse or nearly transverse to the principal vectors of these ebb and flood currents.

The sand waves display a strong asymmetry, with lee slopes facing west to southwest. The angle of the lee slopes generally range between 5° and 10°, although upper crest sections of the lee slopes on some waves may be much steeper, with angles of up to 24°. The stoss slopes are much gentler, and have angles generally less than 3°. Asymmetries of active bedforms are indicative of migration in the direction of the steeper slope, i.e. the lee slopes. However, active bedforms usually have lee slopes closer to the angle of repose of sand, which is typically 20-30°. This suggests that the larger waves could be immobile as the lee slope angles are, in general, less than 10°, however the upper parts of the lee slopes are steep enough to allow sediment to avalanche down the slope.

Although the sand waves themselves comprise medium to coarse grained sand, the sea bed surrounding these features tends to be slightly coarser consisting of gravelly sand or sandy gravel. Between the sand waves, the overall topography of the sea bed tends to be relatively flat.

Figure 3 and 4 illustrate a large west facing sand wave up to 18 m high, the crest is at a minimum depth of 30 m with the trough at the base of the lee slope at a depth of 48 m. This gives a sand wave height to maximum water depth ratio of 0.38. The ratio for minimum water depth at crest height is 0.6. The sidescan mosaic has been draped over the multibeam sea bed surface to produce a 3D image of the sand wave. The stoss slope is covered by sand ripples which are tens of centimetres high and some megaripples around 0.5 m high. These are being driven westward up the stoss slope by ebb currents and cut across the large NNE-SSW trending sand wave crest at a slight angle to the south west.

Megaripples up to 0.5 high, are also well developed on the steep lee slope, however these are aligned across the slope and face north east indicating that sediment on the lee slope is mobile and being transported to the northeast along the lee slope driven by eastward flowing flood tidal currents. The form of the large sand wave appears to be maintained by the interaction of both ebb and flood currents which have produced a pseudo-clockwise motion of sediment movement around the sand wave crest.

Although sand ripples and megaripples indicate that sediment within the top 0.5 to 1.0 m surface of the sand wave is mobile their opposing alignments suggest that the overall structure and position of the large sand wave is being maintained by the interaction of ebb and flood currents and these large sand waves are not moving westward but are in a state of in-situ equilibrium.

To test whether these large sand waves are mobile or immobile requires a comparison to be made of sand wave position and orientation over as long a time period as possible. The study contracted the UK Hydrographic Office (UKHO) to digitise soundings from survey sheets produced from a single beam echo sounder survey run across the area of the OBel Sands in 1977 (Fig. 2).

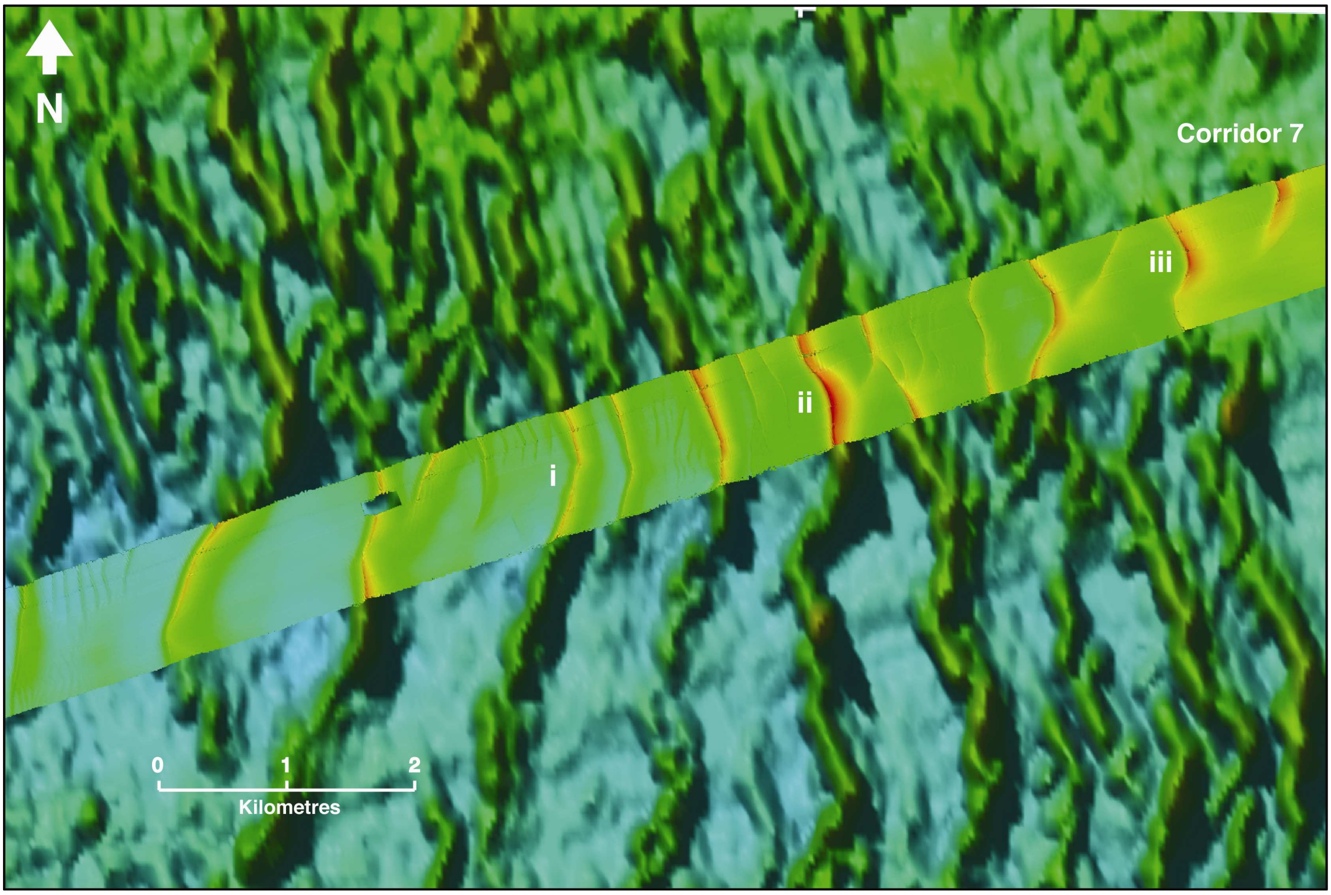

Figure 5. UKHO bathymetric data from 1977 survey overlain with 2003 multibeam corridor 7 survey. ©NERC/NMW/British Crown/SeaZone Solutions

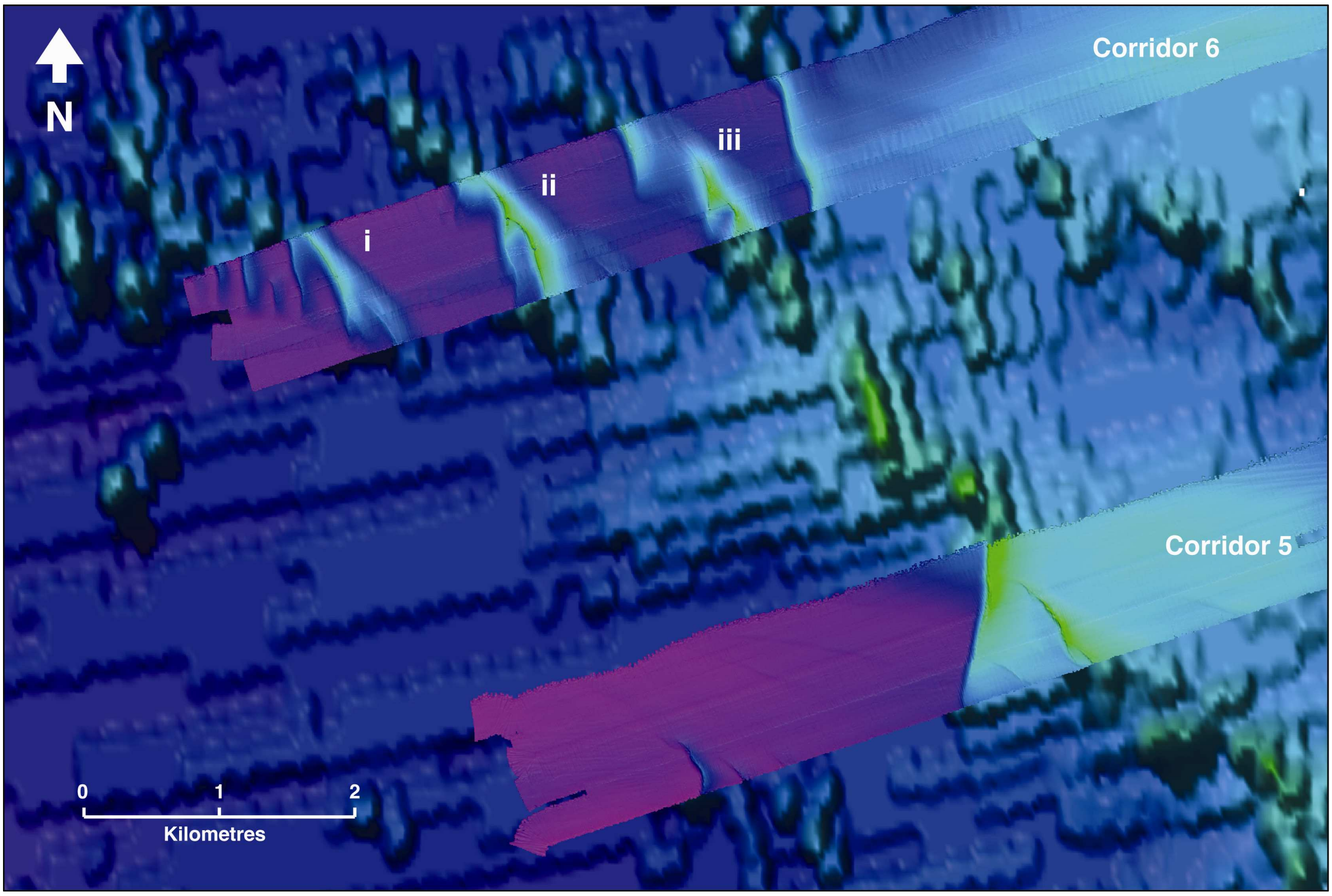

Figure 6. UKHO bathymetric data from 1977 survey overlain with 2003 multibeam corridor 5 and 6 survey. ©NERC/NMW/British Crown/SeaZone Solutions

These soundings are at 50 m spacing but the crest lines of the large sand waves have been preferentially targeted with soundings (C. Howlett, UKHO pers com) so each large wave is within the dataset. The 1977 echo sounder data was processed to produce a sea bed morphology (Fig. 2) which indicates the extent, position and orientation of the large sand waves. This data was loaded into ArcGIS in their georectified positions for comparison with the multibeam corridor data collected in 2003 and 2004. Although the latter is a higher resolution data set valid comparisons can be made and examples of the two datasets overlain on each other are shown in Figure 5 and 6.

The indications of this comparison are that over the 26 years between 1977 and 2003:-

- The number of large sand waves in the area have not increased or decreased.
- The position and orientation of the large sand waves appears to have remained stable with no significant movement of the crest lines.
- There appears to be no growth in sand wave development at the western end of the sand wave field. This might be expected if sediment was being transported across the OBel Sands by the ebb dominant currents from east to west.
- Unfortunately the 1977 survey does not cover the eastern margin of the OBel Sands therefore we cannot see whether there is a loss of sediment at this eastern margin. This might be the case if there is no sand being supplied from further east in the Bristol Channel which is covered by a sediment starved sea bed of rock and lag gravel.

Sand wave heights show only minor variations. At the locations marked i, ii and iii on Figure 5 the heights were recorded as 14m, 16m and 12 m respectively for 2003 compared to 16 m, 17 m and 12 m for 1977. Similarly, on Figure 6 the heights at i, ii and iii were recorded as 12 m, 17 m and 14 m respectively for 2003 and 12 m, 16 m and 15 m for 1977.

In the SOBel Sands the commonly isolated sand waves are generally less than 10 m high with wavelengths ranging from 150 m to 1800 m. The majority of sand waves crests lie in water depths of 40 m, with a relatively flat sea bed between the waves at around 45 m. The sand waves are oriented approximately normal to the peak tidal currents (ranging from NNW-SSE to north-south) and have a strong asymmetry, with the lee slopes facing west to southwest. The angle of the lee slope ranges between 5° and 10°, although smaller sections of the lee slopes on some waves have steeper slopes, with angles of up to 18°. The stoss slopes are much gentler with angles of less than 3°.

The sidescan data indicate that megaripples occur on both the stoss and lee slopes of the < 10 m sand waves. These megaripples are often oriented obliquely to parts of the sand wave crests, suggesting that the orientation of the megaripples is determined by the local flow conditions over the larger waves and not solely by the residual tidal currents

4 DISCUSSION

The NOBel and SOBel Sands are within an area of west flowing ebb current dominance. The peak surface tidal stream velocities at spring tides are greater on the ebb than the flood and ebb dominance is also confirmed in tidal current modelling (Uncles, 1984; Posford Duvivier & ABP Research, 2000; HR Wallingford, 2002). The principal sand waves (~5 – 20 m high) within the NOBel and SOBel Sands are generally asymmetrical with west facing lee slopes. The east facing shallower and generally longer stoss slopes of these large sand waves are commonly covered by megaripples up to 1 m high and smaller sand ripples. The sand waveforms covering stoss slopes are also asymmetrical in cross section with steeper lee slopes facing west. These megaripples and ripples seem to be one of the principal mechanisms of sediment transport across the NOBel and SOBel Sands as they move westward up the stoss slopes of the major sand waves under the influence of the ebb dominant residual currents and avalanche over the steeper west facing lee slopes. The tidal current and bedform evidence appear therefore to be complimentary and indicating net sand transport in the NOBel and SOBel to be in a westerly direction.

The long-term response of the large asymmetrical sand waves should therefore be a steady growth and migration westward. The evidence from seismic reflection records illustrates foreset development in the internal structure of many of the large sand waves and indicates they have undergone steady growth and westward build up of their lee slopes during formation to their current height and position. Their growth is a response to the tidal current conditions and sediment supply prevalent during the last ~5000 years, the approximate period since sea level reached its present level in the Bristol Channel.

Although there is seismic evidence of growth in height and volume of these large asymmetric sand waves, the evidence for their continuing westward migration in present day conditions is inconclusive. They are large structures which are major obstacles to current flows, both ebb and flood currents. Those sand waves that are greater than 10 m in height have crests in water depths of about 25 to 35 m. The height to water depth ratio of these large sand waves is relatively small and their physical impact is therefore relatively great. The processes which control the present day structure of one large 18 m high sand wave described here, include both ebb and flood currents, and although the surface of the sand wave is mobile, the structure and position of the large sand wave is being maintained by the opposing tidal currents suggesting that the large sand waves are not moving westward under the influence of ebb tidal dominance but are in a state of *in situ* equilibrium.

Further evidence from the comparison of bathymetric data collected in 1977 and 2003 indicates the large sand waves in the NOBel and SOBel Sands have remained stable during this 26 year period. This is a relatively short period in terms of geological time but in a dynamic environment such as the Outer Bristol Channel with strong currents and well-developed ebb tidal asymmetry some indication of sand wave migration, growth or loss should be evident. The fact that the available evidence suggests the large sand waves appear to be stable, over at least recent decades, is therefore significant. This also suggests that there is little or no mobile sediment being introduced into the sand wave field from the east.

5 ACKNOWLEDGEMENTS

This paper is based on research undertaken for the Outer Bristol Channel Marine Habitat Study. The two principal funding bodies for the study were the Aggregate Levy Sustainability Fund for Wales, which is administered by the Welsh Assembly Government and the Sustainable Land Won and Marine Dredged Aggregate Minerals Programme of the Aggregate Levy Sustainability Fund in England. The National Museum of Wales (NMW) and the British Geological Survey have contributed from their own research programmes and made funding available for surveys. The Natural Environment Research Council provided ship time for one of the geophysical surveys. The Crown Estate and the British Marine Aggregate Producers Association (BMAPA) provided some funding and contributions of data. The Maritime and Coastguard Agency kindly provided multibeam survey data and Chris Howlett of the UKHO was instrumental in digitising the 1977 echo sounder survey data. Sally Philpott, Angela Morando and Gareth Jenkins of BGS, Andy Mackie, Teresa Darbyshire and Kate Mortimer of NMW and Ivor Rees of Bangor University are thanked for their contribution to the marine habitat study. The author publishes with the approval of the Director, British Geological Survey.

6 REFERENCES

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

Harris, P. T. & Collins, M. B. 1985. Bedform distributions and sediment transport paths in the Bristol Channel and Severn Estuary, U.K. —*Marine Geology* 62(1-2): 153-166.

Harris, P. T. & Collins, M. B. 1991. Sand transport in the Bristol Channel: bedload parting zone or mutually evasive transport pathways? —*Marine Geology* 101(1-4): 209-216.

HR Wallingford 2002. Dredging on Nobel Banks (Area 476), Bristol Channel. Coastal Impact Study Report EX 4597. HR Wallingford, Wallingford.

Institute For Marine Environmental Research (IMER) 1974. Annual Report for 1973-74. IMER, Plymouth. 71 pp.

James, J.W.C., Philpott, S.L., Jenkins, G.O., Mackie, A.S.Y., Darbyshire, T. and Rees, E.I.S. 2004. Outer Bristol Channel Marine Habitat Study – 2003 Investigations and Results. *British Geological Survey Commissioned Report* CR/04/054

Mackie, A.S.Y., James, J.W.C., Rees, E.I.S., Darbyshire, T., Philpott, S.L., Mortimer, K., Jenkins, G.O. and Morando, A. 2006. The Outer Bristol Channel Marine Habitat Study. *BIOMOR Reports* 4. Amgueddfa Cymru - National Museum Wales, Cardiff. 250 pp. & appendix 228 pp.

Pingree, R. D. & Griffiths, D. K. 1979. Sand transport paths around the British Isles resulting from M2 and M4 tidal interactions. *Journal of the Marine Biological Association of the United Kingdom* 59: 497-513.

Posford Duvivier Environment & ABP Research 2000. *Bristol Channel Marine Aggregates: resources and constraints research project. Final Report*. Posford Duvivier Environment, Peterborough.

Shaw, T. L. 1980. Physics of water movement in the Severn Estuary. In *An environmental appraisal of tidal power stations: with particular reference to the Severn Barrage* (ed. T. L. Shaw): 1-36. Pitman, London.

Stride, A. H. & Belderson, R. H. 1990. A reassessment of sand transport paths in the Bristol Channel and their regional significance. —*Marine Geology* 92(3-4): 227-236.

Uncles, R. J. 1982. Computed and observed residual currents in the Bristol Channel. —*Oceanologica Acta* 5: 11-20.

Uncles, R. J. 1984. Hydrodynamics of the Bristol Channel. —*Marine Pollution Bulletin* 15(2): 47-53.