MARINE SAND AND GRAVEL PROSPECTING AND SEABED INVESTIGATIONS FOR AGGREGATE EXTRACTION

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Abstract

Exploration for marine sand and gravel relies on a combination of regional scale palaeo-geographical reconstruction of the continental shelf using existing literature and secondly on the acquisition of high resolution shallow seismic profiles, side scan sonar and multibeam bathymetric data from specific seabed sites. Prospecting sites are chosen not only for their geological potential but also with regard to water depth, distance from the aggregates market and whether there are any significant conflicts with other marine activities or nature conservation areas. Reconnaissance level charts and seabed characterisations by the British Geological Survey and others are used before decisions are made over areas to be surveyed in detail to determine whether economically viable sand and/or gravel aggregates are present. The marine aggregates industry continues to favour 2D analogue and digital boomer seismic profile data as the primary means of investigating the shallow geology beneath the seabed and interpretation of this data is assisted using traditional vibrocore sampling, with sample sites carefully chosen from an initial seismic interpretation. In addition investigations are assisted by the now routine use of multibeam echo sounding as a means of obtaining complete coverage of the sea floor bathymetry to resolve surface features with a resolution of under 0.3m. The combination of these datasets assists not only in assessing geological potential for sand and gravel but also in drawing up dredging extraction plans, monitoring resource usage and in establishing mineral reserve and resource volumes.

Bellamy, A.G. 2018. Marine sand and gravel prospecting and seabed investigations for aggregate extraction. Pp. 205-215 in Hunger, E., Brown, T. J., Smith, G. and Anderson, P. (Eds.) Proceedings of the 19th Extractive Industry Geology Conference 2016 and technical meeting 2017, EIG Conferences Ltd, 256pp.
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Introduction

This paper examines how marine aggregates are located and extracted on the continental shelf off the UK. Extraction by the dredging of these natural sand and gravel deposits takes place in over fifty licensed areas in the North Sea, English Channel, Bristol Channel and Irish Sea (Figure 1).

The following topics are covered in this paper:

- the stages involved in narrowing down the search area from the UK seas scale, which covers some 850,000 km^2, to a manageable survey area of a few tens of square kilometres,
- the factors affecting the choice of aggregate prospecting areas by operating companies,
- how the data from site surveys is interpreted, plotted and charted,
- how dredging extraction plans are devised,
- the factors affecting the ease of dredging ('dredgeability') in a given area, and
- the monitoring of mineral resource usage during the term of an extraction licence.

Locating Marine Aggregates On The Continental Shelf Off The UK

Geological background

An appreciation of the geological history of the seabed is needed to evaluate the likelihood of locating sand and gravel deposits in a particular area. Marine aggregates are unconsolidated sands and gravels (Figure 2) formed primarily during the Quaternary Period, like their land-based counterparts. Over this approximately two million year long episode of Earth history, the UK continental shelf has experienced not only marine conditions as at present, but also cold and temperate climate terrestrial environments arising from climatic and sea level changes. For most of the Quaternary, sea level was lower than at present as demonstrated by oxygen isotope records (James *et al*., 2011 (Figure 54)) and our status as an island nation is atypical of much of the Period. Instead, the British Isles formed an extension of the northwest European mainland for much of Quaternary time, with the present shallow seabed of the inner continental shelf exposed as land. This is illustrated in the hypothetical reconstruction in Figure 3 which demonstrates that during the last glacial maximum 20,000 years ago, sea level was over 100m lower than present (Catt *et al*., 2006),

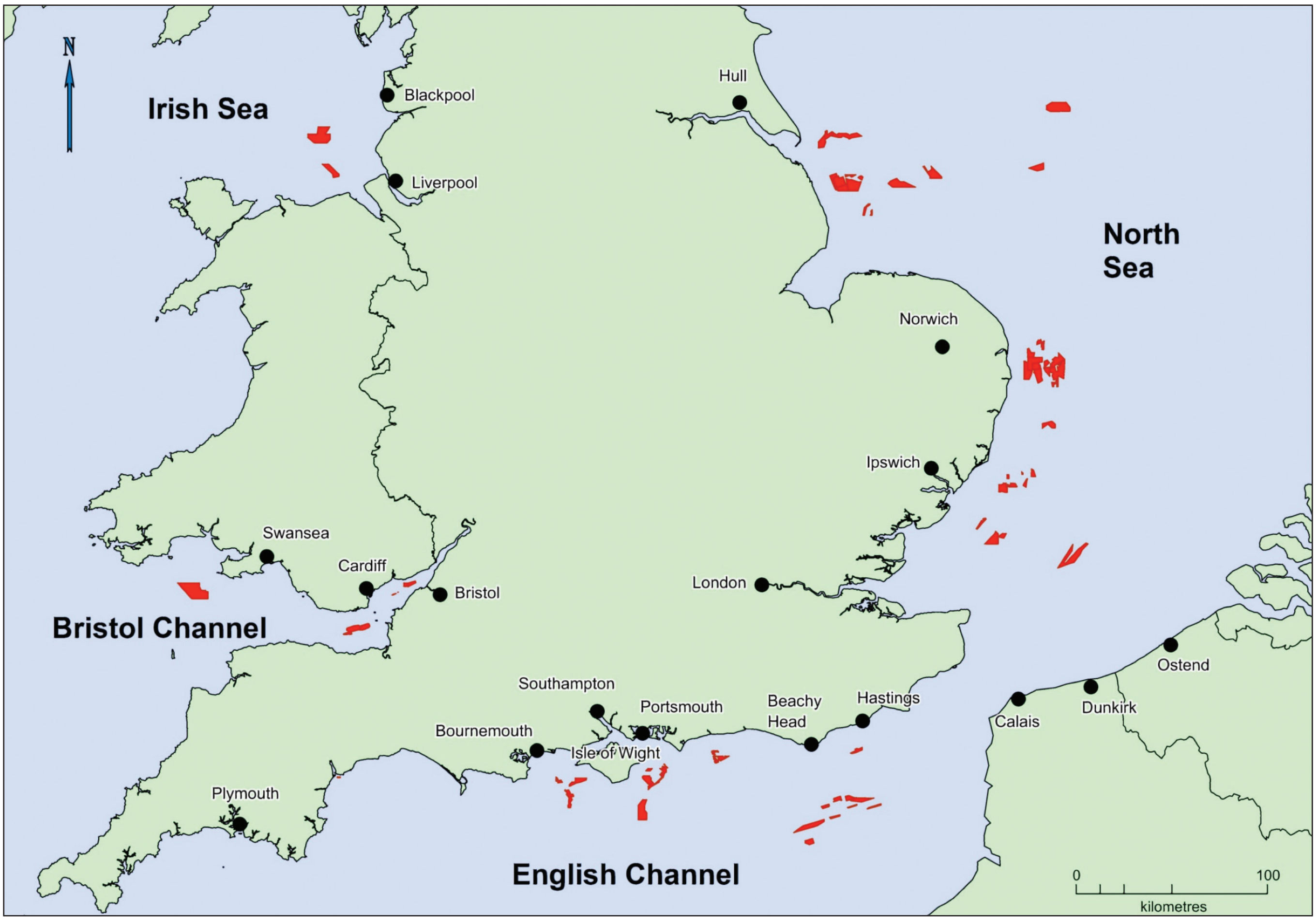

Figure 1. *The location of aggregate dredging licence areas (shown in red) off the UK in 2017.*

exposing much of the present-day seabed off southern Britain as land, with an ice sheet over much of northern Britain, the present Irish Sea and central-northern North Sea.

Beyond glacial ice limits, the extension of rivers onto the exposed continental shelf in cold stages of the Quaternary led to the accumulation of sands and gravels over braided channel floodplains in periglacial environments analogous to arctic Canada or Siberia. Marine aggregate prospecting off southern Britain has focussed on the preserved 'palaeovalley' networks that these rivers eroded and infilled over prolonged and repeated episodes of lower than present sea level (Figure 2). Fluvially derived gravelly marine aggregates are especially well developed where Cretaceous Chalk occurs within former river catchments, with almost all of the floodplain gravel being composed of durable flint, derived from the easily eroded and water-soluble chalk. For this reason the palaeovalleys of the Thames and its tributaries, the Norfolk Yare, the Sussex Arun, the Solent River network and the palaeovalleys of the eastern English Channel either have been or are exploited for marine aggregates (Emu Ltd, 2009; James *et al.*, 2011; Limpenny *et al.*, 2011).

Glacially derived sands and gravels occur within the limits of the last ice sheet which extended over the British Isles and the adjacent offshore area during the Late Devensian stage (Bowen *et al.*, 1986). Most aggregate deposits dredged off the Humber are derived from either the glacial till of the Bolders Bank Formation (Tappin *et al.*, 2011) or wind-blown sands of the Twente Formation (Cameron *et al.*, 1992), lying to the south of the ice limit. In the Humber region, a combination of fluvio-glacial and marine reworking has removed the fines fraction, leaving commonly well rounded, fine to coarse grained gravels and medium to coarse grained sands (BMAPA and The Crown Estate 2015). The glacial derivation is evident in the mixed lithologies of these deposits, which consist of diverse rock types mainly originating from sedimentary rocks outcropping in eastern England (Tappin *et al.*, 2011), with flint representing only a small part of the assemblage, in contrast to the predominantly flint deposits of the English Channel and off East Anglia.

Marine transgression towards the end of the last glacial stage led to the submergence of the landscape off southern Britain as the coastline retreated across the continental shelf. The low relief of much of the continental shelf meant that only a small rise in sea level submerged a relatively large area, with river valleys becoming estuaries and then inter-tidal marine inlets before fully marine conditions became established. Estuarine sedimentation has blanketed periglacial sand and gravel with overburdens of fine-grained sediment in several marine aggregate localities in the eastern English Channel and in the southern North Sea.

An important effect of the last marine transgression was the reworking of surficial fluvial and glacial sediments to form seabed sediment veneers covering large expanses of bedrock. In addition, transgression led to the formation of sand banks and sand wave fields as tidal currents and storm waves began to affect sediment transport. Sand banks and sand waves represent locally important sources of marine aggregates, notably in the Bristol Channel, outer Thames Estuary and off Lincolnshire. Bank systems formed from marine reworking of pre-existing glacial, aeolian or fluvial sand deposits. In the Bristol Channel, large headland attached banks such as the Nash and Helwick Banks off south Wales and mid-channel banks such as Culver Sands have formed in response to the strong tidal regime of the region and have been sources of marine aggregate for much of the past century.

Marine aggregates are also extracted from the south-eastern Irish Sea (Figure 1). The region was glaciated during the Devensian stage leaving spreads of till composed of stiff, pebbly clays and thick glacio-marine and lagoonal sediments (James *et al.*, 1992). However sands dredged in Liverpool Bay likely relate to deglaciation, accumulating during a relatively short terrestrial interlude between glacial ice cover and marine transgression. This episode allowed the development of a wide river floodplain across present-day Liverpool Bay, associated with the ancestral rivers Mersey and Dee (Figure 2). The floodplain sediment is sand-rich, locally

Figure 2. *A summary of the origins of land-won and marine sand and gravel in southern Britain.*

over 10m thick and is a major source of marine dredged aggregates today.

Geological data sources

Mapping by the British Geological Survey

Reconnaissance level shallow seismic and core and grab sampling surveys by the British Geological Survey (BGS) since the 1970s have produced a wealth of excellent information on the composition and thickness of seabed sediments across much of the UK continental shelf. In the late 1980s the Crown Estate commissioned a series of marine aggregate survey reports in the southern North Sea, English Channel and Irish Sea which proved useful in identifying areas of interest (eg. Balson and Harrison, 1988). More recently, BGS has produced a series of reports, charts and shape-files of marine aggregate resource potential for the Crown Estate which updates the mapping and expands the coverage of the work done in the 1980s (eg. Bide *et al.*, 2013). Regions covered include the English Channel, southern North Sea and Irish Sea and the work is assisting with marine planning by the Marine Management Organisation. In addition, BGS has played a major part in marine environmental characterisation studies, funded from the Marine Aggregate Levy Sustainability Fund, for example James *et al.,* (2010), and these too have proven to be invaluable sources of reconnaissance level data for marine aggregate investigations.

The use of Hydrographic Office charts

Navigational charts produced by the Hydrographic Office (HO) for mariners have proved useful in helping to search for marine aggregates. As well as showing the

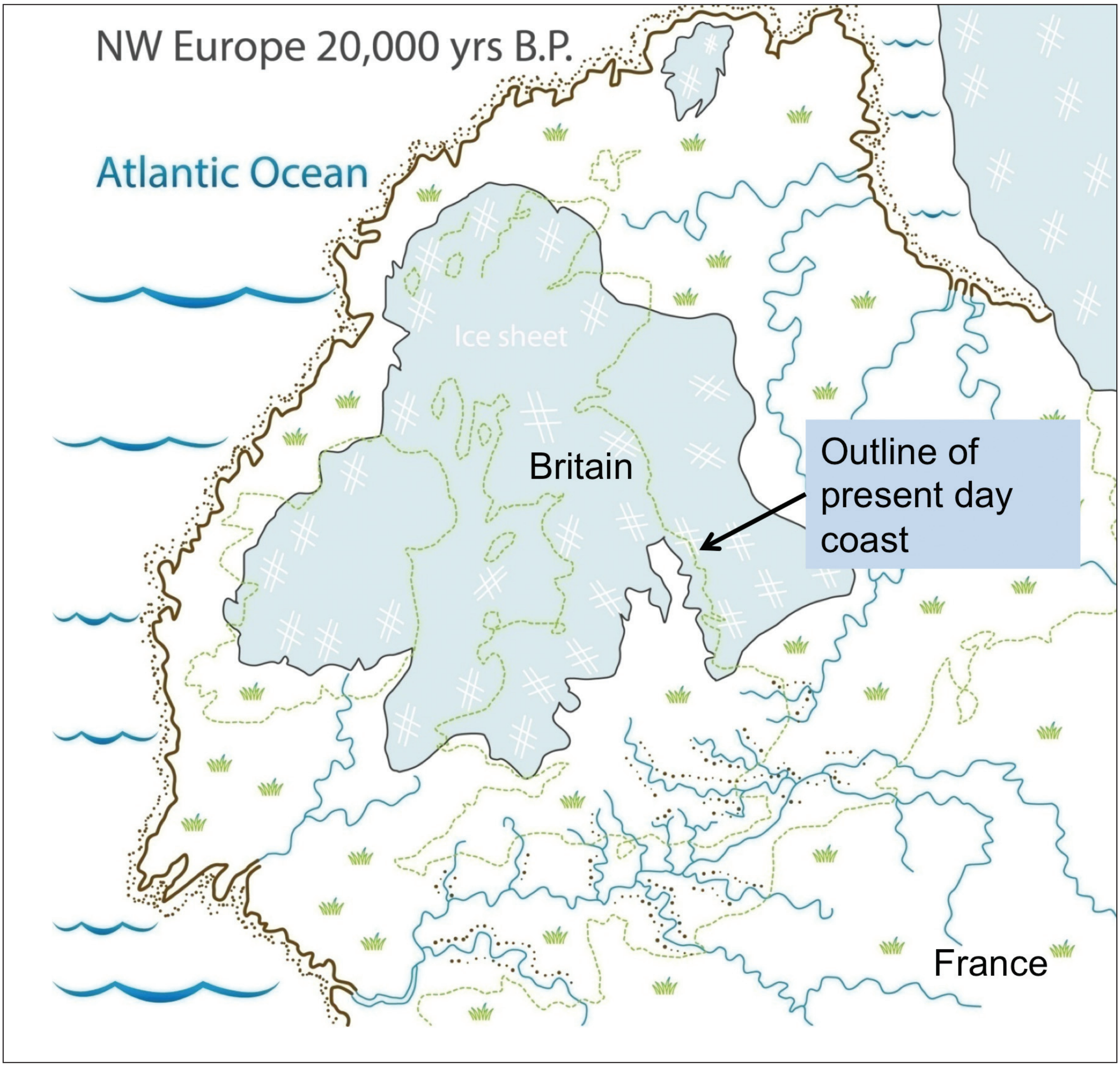

Figure 3. *Hypothetical reconstruction of the British Isles during the last glacial maximum 20,000 years ago, showing known ice sheet limits (pale blue hatch) over much of northern Britain, the present Irish Sea and central-northern North Sea.*

location of ship wrecks, sampled seabed sediments and important navigational aids, the charts show spot soundings of water depths taken over the past few decades. The charts highlight banks, shoals and named marine features which can suggest marine aggregate locations. For example, the chart for the eastern English Channel shows the 'Hastings Shingle Bank 10km off Hastings (Figure 4). Geological surveying has since shown this feature to be one of the largest gravelly aggregate deposits off the south coast.

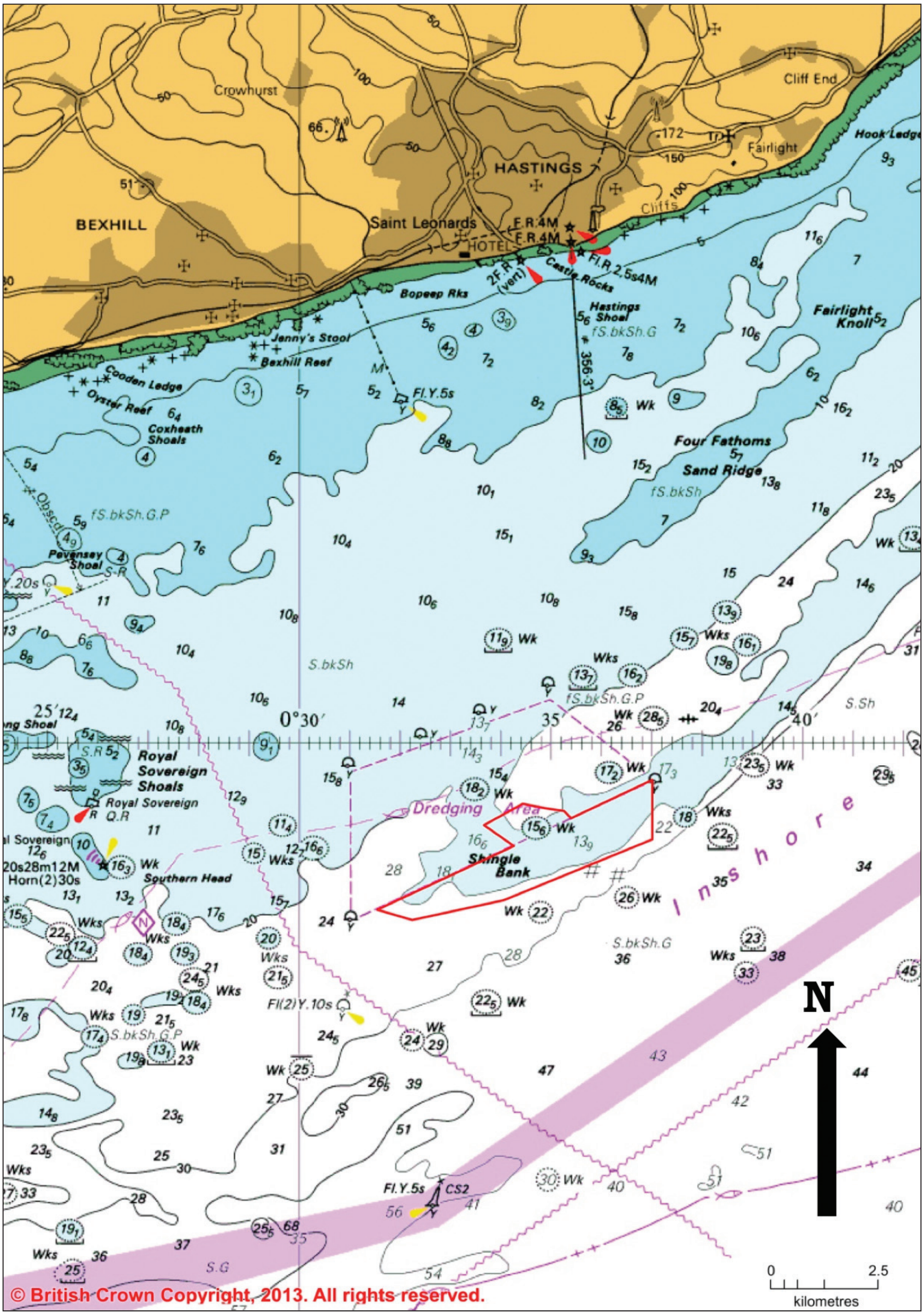

Figure 4. *Hydrographic Office chart showing the Hastings Shingle Bank and the licensed aggregate dredging area (bound by the red line).*

Prospecting for aggregates by the industry

In contrast to the broad-scale surveys carried out by the BGS over the years, industry surveys typically cover much smaller areas but survey in somewhat more detail to identify the thickness, extent and geometry of specific aggregate deposits. The choice of search area is commonly directed by the BGS and HO data and a detailed survey is then necessary to provide the resolution required to identify extractable marine aggregates and areas of unproductive seabed. Whilst the seismic line spacing for a typical 100km² reconnaissance survey would be commonly 0.5 – 1.5km or more, a line spacing of 250m or less is common for an aggregate prospecting survey, yielding much more detailed data on the shallow geological characteristics. Geological surveys for marine aggregates rely on a combination of multibeam bathymetry, high resolution shallow seismic profile data combined with grab and vibrocore (borehole) sampling.

Multibeam echo sounder data (Figure 5) enables complete coverage of the sea floor bathymetry to resolve surface features with a resolution of under 0.3m. This is a great improvement on the older single beam systems where relatively little could be resolved except for a basic representation of the bathymetry that relied on extrapolation between survey lines. Multibeam data provides a sound baseline for dredging depth and resource usage monitoring over the term of an extraction licence and highlights major features such as sandbanks and sandwaves (Figure 5) which can form high quality marine aggregate resources. However, echo sounder data does not reveal what is beneath the seabed so high resolution shallow seismic data, usually 'boomer' or 'pinger' is collected for this purpose.

Boomer and pinger data provides an acoustically generated cross section of the shallow geology (Figure 6), with a resolution of less than 0.5m and a penetration for aggregate investigations of typically less than 20m below the seabed. The collection of this data requires survey vessels crewed by specialist survey contractors with a combination of electronic, navigational and geological skills. The interpretation of shallow seismic data requires knowledge of the geological context of a given area and an understanding of the methods of data acquisition so that 'true' geological features can be differentiated from artefacts produced by the seismic system. BGS has published an 'atlas' of seismic signatures which provides a good source of information on data types and how data is successfully interpreted (Evans *et al.*, 1995). For aggregate assessments, data is interpreted to record the thickness and extent of aggregate deposits, their geometry and relationships with the bedrock and any finer-grained sediments that might contaminate the aggregates during dredging operations. Interpretation is assisted using core samples from carefully selected locations chosen from the seismic interpretation. Core samples are recovered using a

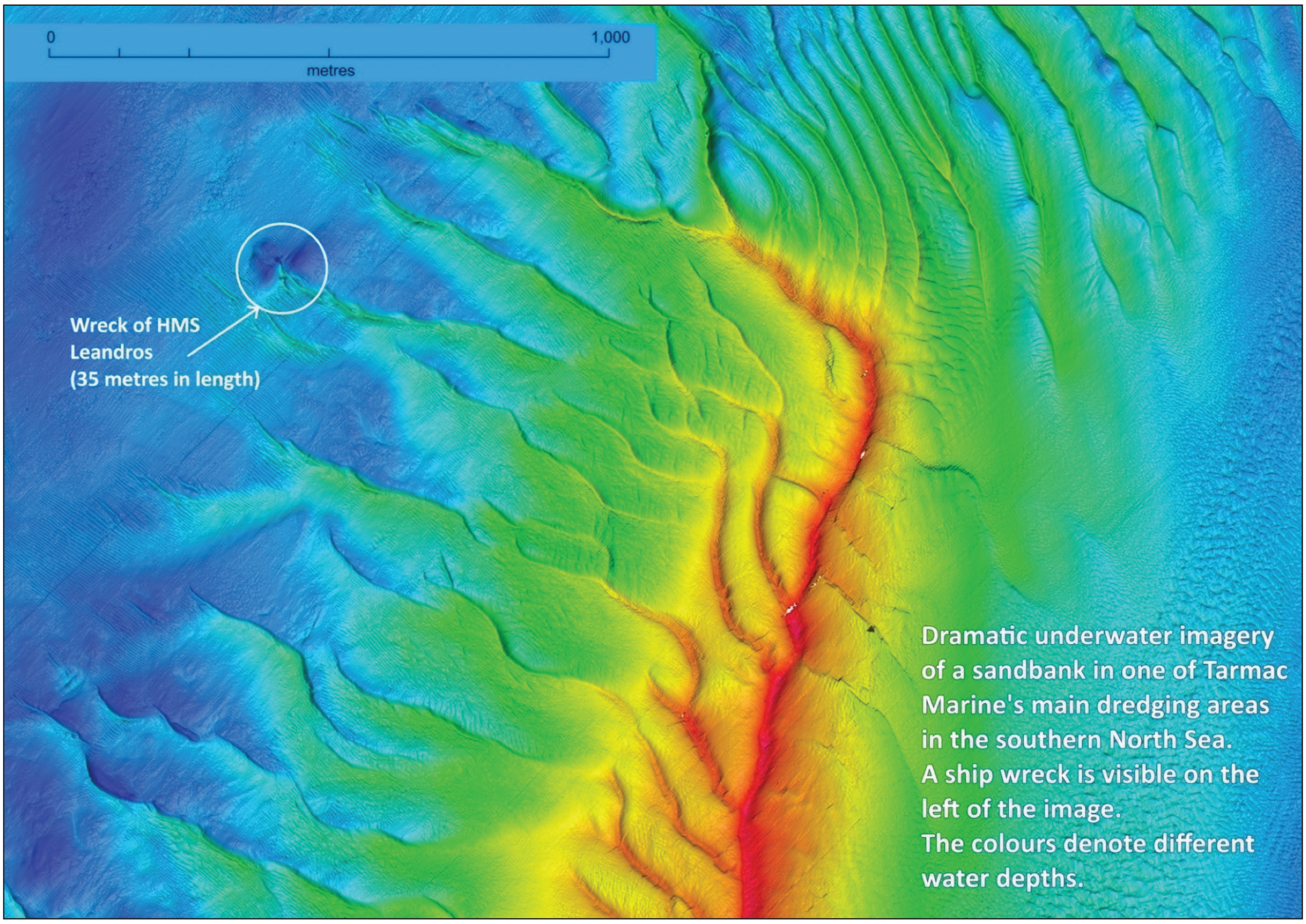

Figure 5. *Multibeam echo sounder image of the seabed in a licensed dredging area in the outer Thames Estuary showing the northern margin of the Kentish Knock sandbank with its associated sandwaves and a ship wreck to the west.*

vibrocorer which consists of a 3m, 4m or 6m core barrel with plastic liner, attached to an electric or hydraulic motor in a tripod frame. The corer is lowered to the seabed from a survey vessel and a sample is obtained within a few minutes when the barrel is forced into the seabed as the motor is activated from controls on the deck of the survey ship. Once the corer is lifted back to the sea surface, the core liner is removed from the barrel on deck and the sample within the plastic liner is stored for later analysis ashore. The core sample is then cut

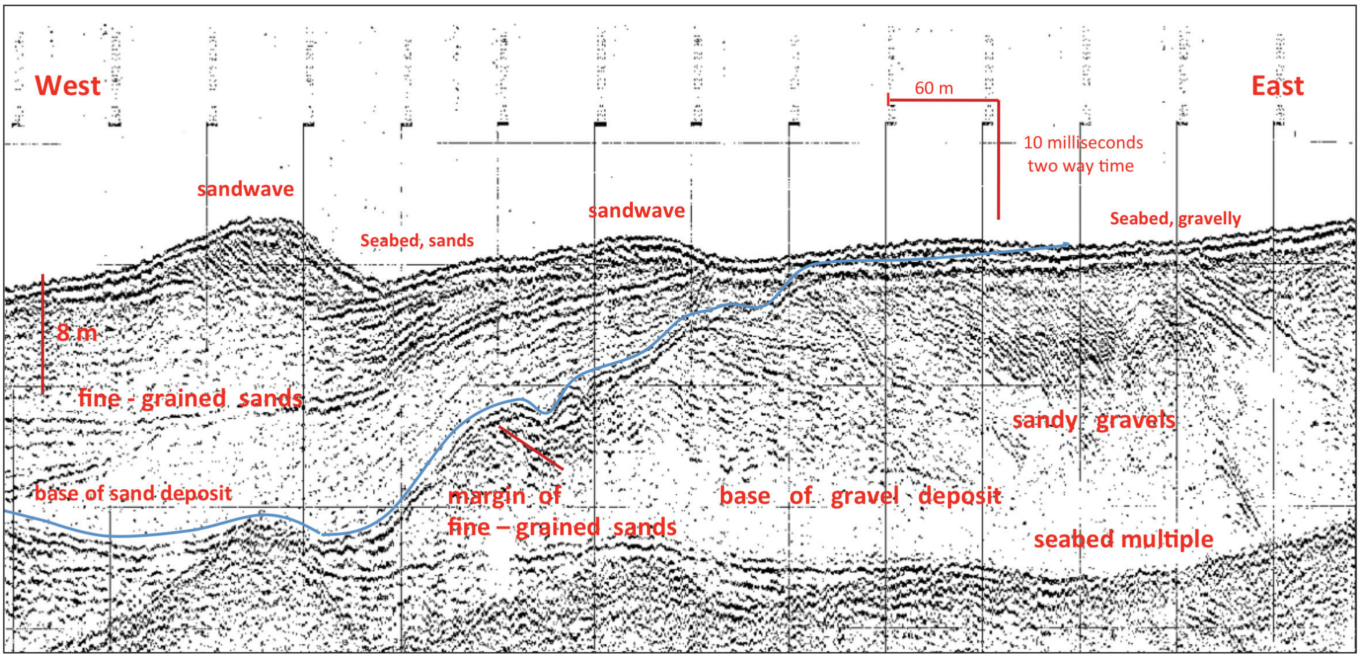

Figure 6. *Example of an interpreted high resolution shallow seismic profile from sediments in the former Solent River floodplain 12km east of the Isle of Wight. Vertical exaggeration x 9.*

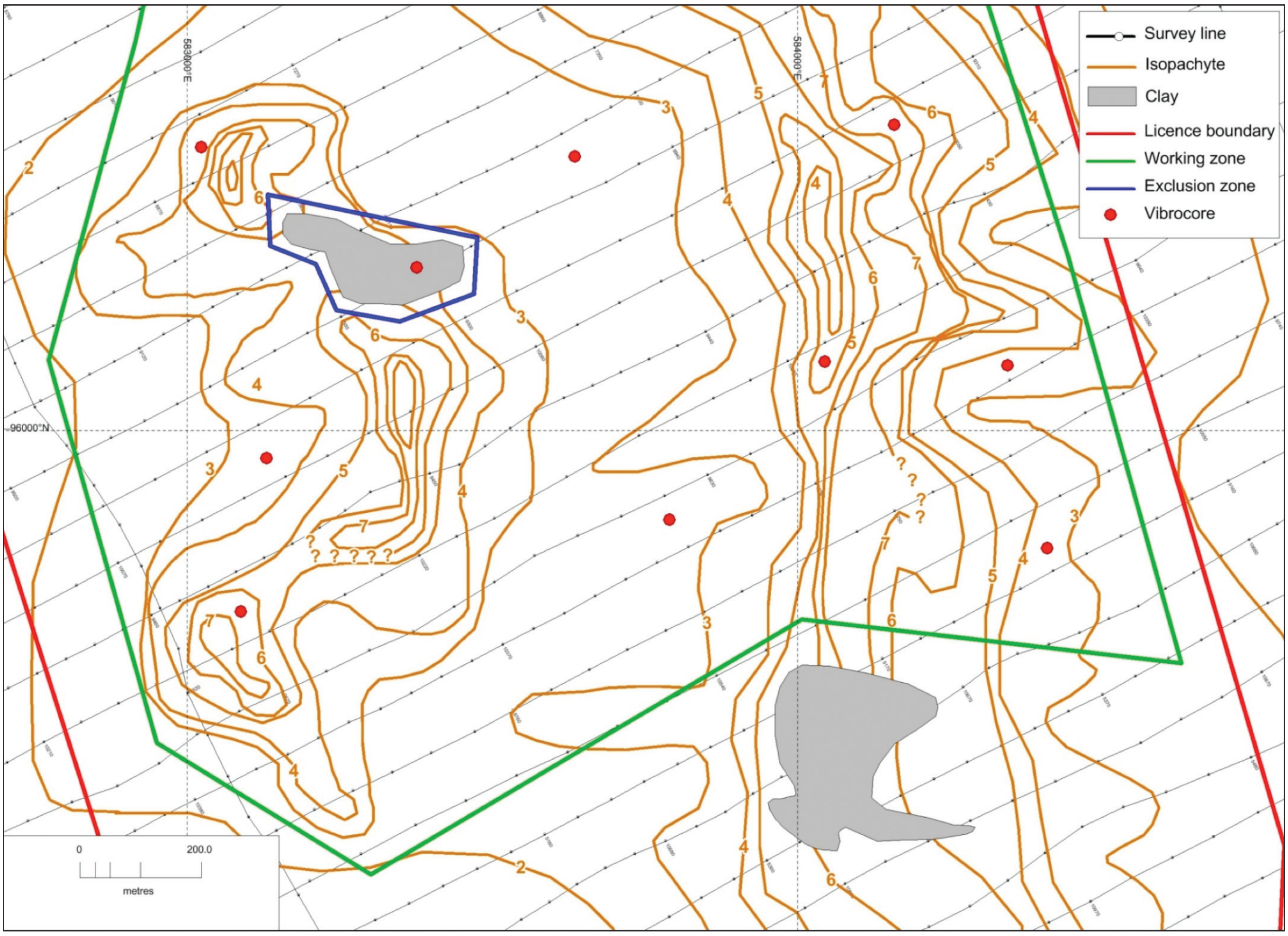

Figure 7. *Example of a seismic survey track chart with hypothetical sample sites, isopachytes and sediment boundaries.*

open, photographed and logged in the laboratory. In addition, particle size analysis is routinely undertaken on several subsamples per core. Core samples demonstrate sediment colour, composition, lithology and grading and can confirm the thickness of sediments overlying bedrock.

Using both seismic and core sample data, deposit margins and sediment spot thicknesses above bedrock can be plotted. Provided that a sufficient density of spot thicknesses is recorded, lines of equal sediment thickness (isopachytes) are plotted and charts produced showing the extent and thickness of aggregate deposits (Figure 7). Seismic interpretation and charting is assisted with reference to sample data, with core sites recorded on isopachyte charts to confirm whether or not seismic interpretation is correct. Once a satisfactory interpretation is made, a decision can be reached on perhaps whether to apply for an extraction licence, or alternatively to implement dredging zones if the area is already licensed for aggregate extraction.

Factors Affecting The Choice Of Prospecting Areas

The following factors determine whether or not a company will decide to commission a survey to search for marine aggregates:

- Geological context – key in determining the likelihood of aggregates occurring in a given site.
- Water depth – this must be neither too shallow nor too deep for dredgers to access the site.
- Steaming distances – the transport distance from the aggregate deposit location to the aggregate market is fundamental in whether an area of seabed might be commercially viable. This factor is considered in relation to the cargo capacity of the dredger and the value of the aggregate, with a larger capacity ship able to travel further on a longer cycle time than a smaller ship.
- Environmental and spatial constraints – Marine Protected Areas (MPAs), designated archaeological sites and other developments such as wind farms and cable routes can preclude marine aggregate extraction. These factors can reduce the area available for dredging or can cause uncertainty over free access to a given area, with the possibility of seasonal restrictions on dredging and/or exclusion zones being required, limiting the area of resource available.
- Proximity to other aggregate licence areas – if a new prospecting site is adjacent to existing licence areas, there might be a greater chance of locating additional resources, if geological boundaries extend over licence areas. This has proven to be the case in the eastern English Channel, where the cluster of dredging licences south of Beachy Head has grown in extent since the mid 1990s (Figure 1).

Dredging Plans And Factors Affecting The 'Dredgeability' Of A Deposit

Dredgers are sent co-ordinates which define a specific loading area within a given aggregate deposit, based on a geological model (Figure 8). These loading areas are usually parallel to the tidal stream and provide sufficient space for the ship to load efficiently while underway (trail dredging) or provide sufficient scope to load at anchor ('static' dredging). Test dredging is commonly carried out to investigate the feasibility of loading with amendments possible to the length of the loading run, its width or orientation. Dredging areas can be divided into lanes to further subdivide a deposit and these can allow more controlled management of extraction operations as a deposit is extracted systematically.

The ease of aggregate extraction by dredgers ('dredgeability') is determined by several factors including:

- *Water depth* – aggregate dredgers in the current UK fleet have dredging depth capabilities ranging from 20m to about 50m.
- *Deposit geometry* – meaning the plan form, thickness variations and extent of a deposit. This determines the shape and extent of the loading area.
- *Substrate type* – London Clay or glacial till substrates present more difficulties in planning a dredging area, being contaminants in aggregates, compared to sand or solid rock.
- *Overburdens and interburdens* – A seabed overburden of fine-grained sediment greater than a few centimetres thick in a marine aggregate context would sterilise a deposit. This is due to the cost and virtual impossibility of removing the overburden over the whole extent of the dredging area (covering typically 500,000m^2 or more of seabed) and subsequently disposing of the sediment in a separate licensed disposal site. An interburden of fine sediment can also present difficulties due to cargo contamination as the deposit is worked. Fortunately, significant interburdens are unusual in marine aggregates off the UK.
- *Length and width of the dredging area* – a short dredging area relative to the size of dredger will increase the loading time as more turns and passes of the area are needed to complete the load. Dredgers are capable of tight turns as Figure 9 shows, but turning can extend the loading time as the dredge pipe is usually lifted clear of the seabed at this time.
- *Tidal stream direction, tidal current strength and exposure to prevailing weather* – strong tidal currents, for example in the Severn Estuary, or exposure to frequent storm waves and swell as in the outer Bristol Channel, will reduce the ease of access to a dredging area. A location sheltered from prevailing winds by land, for example the English Channel just east of the Isle of Wight, will favour extraction in all weathers.

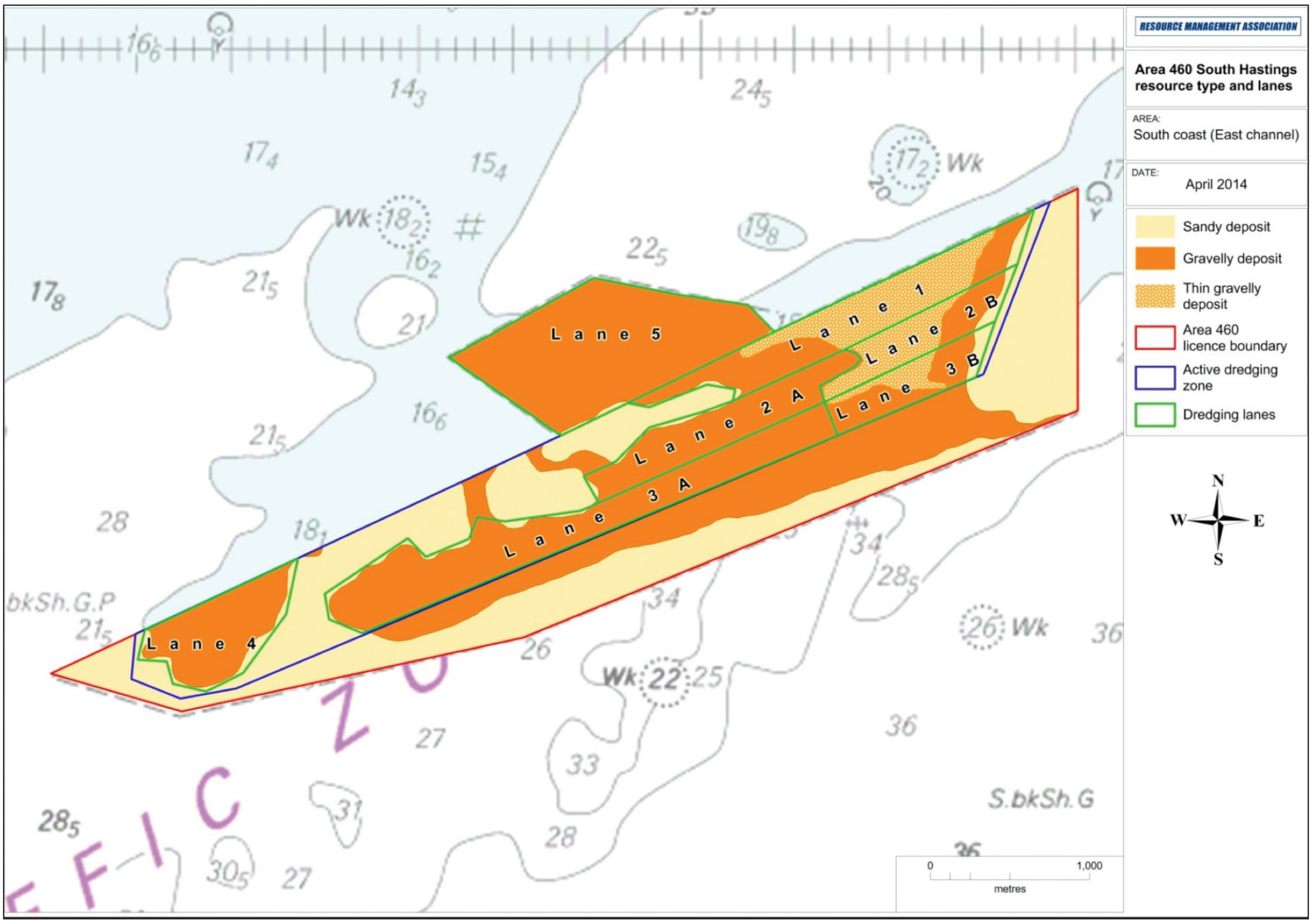

Figure 8. *A dredging extraction plan for the Hastings Shingle Bank licence area, showing loading lanes.*

Figure 9. *The Tarmac aggregate dredger 'City of London' turning during dredging operations in the Hastings Shingle Bank licence area in the eastern English Channel.*

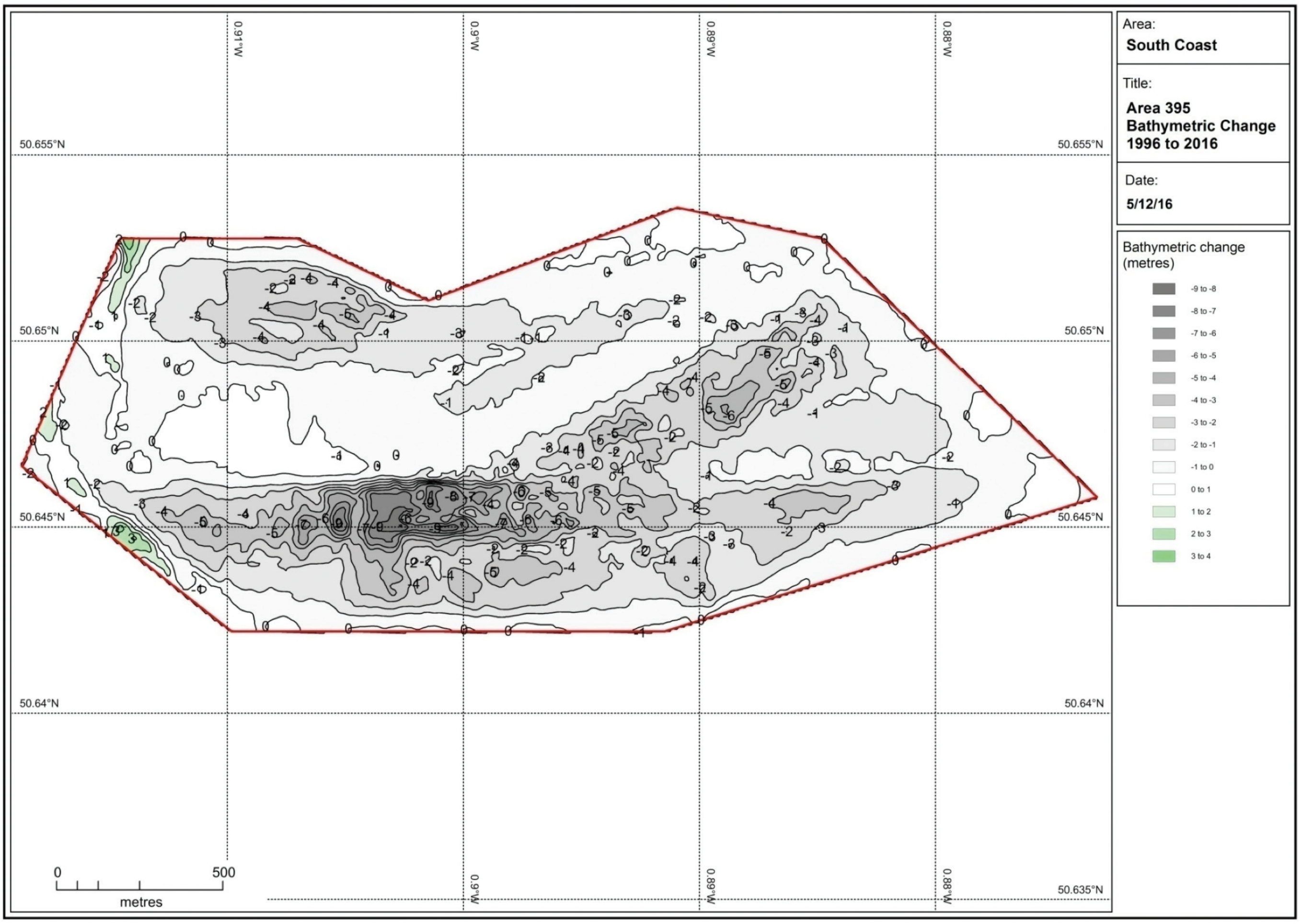

Figure 10. *Bathymetric change, in metres, due to aggregate dredging in licence area 395.*

Monitoring Resource Usage Using Geological Data

Marine aggregate deposits, like their land-based counterparts, are finite resources and once removed will not re-form. Typically a depression on the seabed will remain after extraction ends on a palaeovalley, or, in the case of a sandbank, a reduction in sand volume will be detectable.

Geological data is used to monitor resource usage through the collection of bathymetric and sediment thickness data at regular intervals during the term of all extraction licences. A thorough baseline pre-dredge survey is carried out to define water depth and sediment thickness and subsequent bathymetric surveys are used to predict the thickness of resource remaining as extraction proceeds and water depth increases. Figure 10 is an example from a dredging area 10km east of the Isle of Wight where resource monitoring is undertaken using this technique.

Concluding Remarks

Exploration techniques for marine aggregates are well established, focussing on high resolution shallow seismic and core and grab sample data to establish the extent and thickness of viable deposits. This data has revealed in considerable detail the sediments of the Quaternary Period infilling now submerged river floodplains and valleys, forming glacial outwash and forming sandwaves from sand and gravel reworked during the last marine transgression over the UK continental shelf. This data is also used to monitor the extraction of resources and for compliance with marine licence conditions related to the permitted depth of extraction and the seabed condition after dredging ceases.

Exploration for marine aggregates has proven to be successful over the past few decades with typically around 20 million tonnes of marine sand and gravel extracted per year from UK licence areas. Future reserves exceed 370 million tonnes within the current permissions applying to UK dredging areas (The Crown Estate, 2016), this figure being derived from the geological data and analytical approach outlined in this paper. There is the potential for demand to increase and the industry is projected by the Crown Estate to be landing 29 million tonnes of marine sand and gravel per year by 2030.

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