Technical Appendix 2: The application of extensive 3D Seismic Reflection Data for the exploration of extensive inundated palaeolandscapes

Simon Fitch and Vince Gaffney

In recent years there has been an increasing appreciation of the archaeological significance of the European coastal shelves, their capacity to inform our understanding of early prehistoric settlement and the potential of these areas to retain and preserve archaeological evidence that might be rare or absent within contemporary terrestrial contexts. In part this has been the consequence of technological development. This is hardly surprising as the exploration of landscapes that are supranational in scale and which may be masked by tens of metres of water or sediment provide archaeologists and heritage managers with a unique set of technical and methodological challenges. Marine archaeology, of course, has had recourse to a variety of data sources when exploring marine environment and these may include excavation, where conditions permit, seabed sampling, shallow coring, bathymetric survey, and a variety of remote sensing technologies including seismic reflection profiles. Some of these datasets may have been acquired for a variety of non-archaeological purposes, have differing characteristics and utility. For example, surveys collecting seabed sampling or involving shallow coring can provide detailed chronological, sedimentological and environmental data but frequently have a relatively poor spatial framework. High-resolution bathymetry can provide excellent images of the seabed topography but does not usually represent submerged features that lack a bathymetric expression.

For early prehistory, the requirement for regionally extensive data across the entire area of the continental shelve is such that, aside from precision and contiguity, issues of scale and resolution are also of considerable importance. Currently, it is largely true that only seismic reflection datasets are likely to provide maps for buried Quaternary landscape features at a regional level. However, marine seismic acquisition is also undertaken for a variety of purposes and involves varying data densities, coverage, depths of penetration and resolution. Consequently, there is often a choice to be made when using such data and it is entirely possible that specific surveys may not be appropriate for use by archaeologists with specific research agendas. The decision to use such data will therefore depend upon archaeological requirement and the fit of available data on the grounds of resolution or scale of survey. In many ways this position is not so different to that experienced by terrestrial archaeologists who often have valid reasons to choose spatially extensive, low resolution sensors in preference to high resolution sensors. The latter technologies may often only operate at site level and have little relevance to research that is concerned with the investigation of behaviour at landscape level. Within a marine context, extensive datasets, which are often characterised by low resolution, may not initially appear to support the requirements of detailed archaeological investigation. However, they can provide an invaluable topographic framework to guide detailed work or into which higher resolution survey, shallow boreholes, seabed samples and bathymetric data can be integrated (Gaffney et al. 2007; 2009). These data may also be used within extensive modelling programmes which may not be supported by less extensive datasets. We can explore some of these issues by considering the nature of these data sets and some examples of their recent use.

Seismic reflection surveying involves the transmission of acoustic energy into the subsurface and recording the energy reflected from acoustic impendence contrasts. The reflections produced at acoustic impendence contrasts are predominantly the product of changes in lithology. With appropriate processing this allows the production of pseudo-depth sections of the subsurface structure with the vertical axis being two-way travel time to the reflector. Although the basics of this technique are common, the details vary for a range of applications including the investigation of deep crustal structure, hydrocarbon exploration and near seabed sediment structure (e.g. Salomonsen &

Jensen 1994; Velegrakis et al. 1999; Praeg 2003 and Bulat 2005). These diverse applications dictate different acquisition parameters that in turn determine the resolution and depth of penetration of the survey as well as the costs involved in acquiring the data. Consequently, the relative merits of a range of available seismic reflection data types needs to be assessed when considering the investigation of submerged, and partially buried features.

Standard marine acquisition involves towing an energy source and a cable (streamer), containing pressure sensitive receivers, to record the reflections from the underlying strata (Figure 1). In single fold data, only one reflection is received from any point in the subsurface. However, many seismic profiles are multi-fold and reflections can then be summed in order to increase the signal-to-noise ratio of the seismic profile.

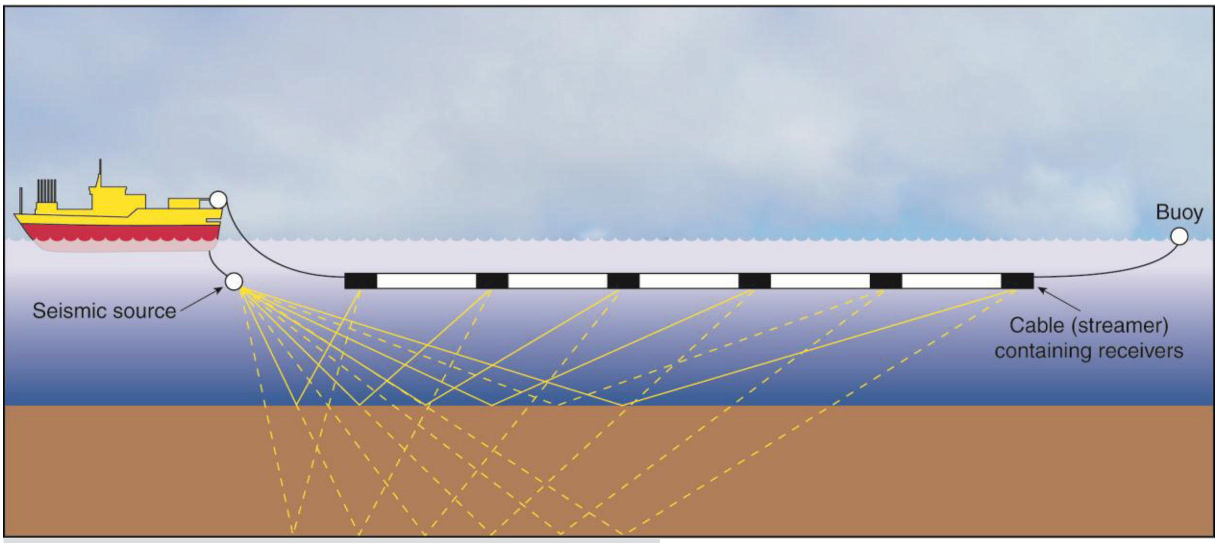

Figure 1: Typical marine seismic reflection acquisition.

Traditional seismic reflection data is generally referred to as 2D as it is acquired as a series of discrete vertical profiles using a single streamer towed behind the vessel. This acquisition pattern results in the collection of several profiles with the spacing between profiles being several orders of magnitude greater than the trace spacing (i.e. the horizontal sampling interval along the profile). This method of acquisition has two main disadvantages. Firstly, the reflected seismic energy is assumed to have originated from a point directly beneath the profile even though it could have originated from a point laterally offset from the profile. Secondly, the spacing between lines may be so wide that it can be difficult to map the position of a morphological feature across the region of interest. For example, Figure 2 (a-d) demonstrates how wide line spacing can lead to several equally valid interpretations.

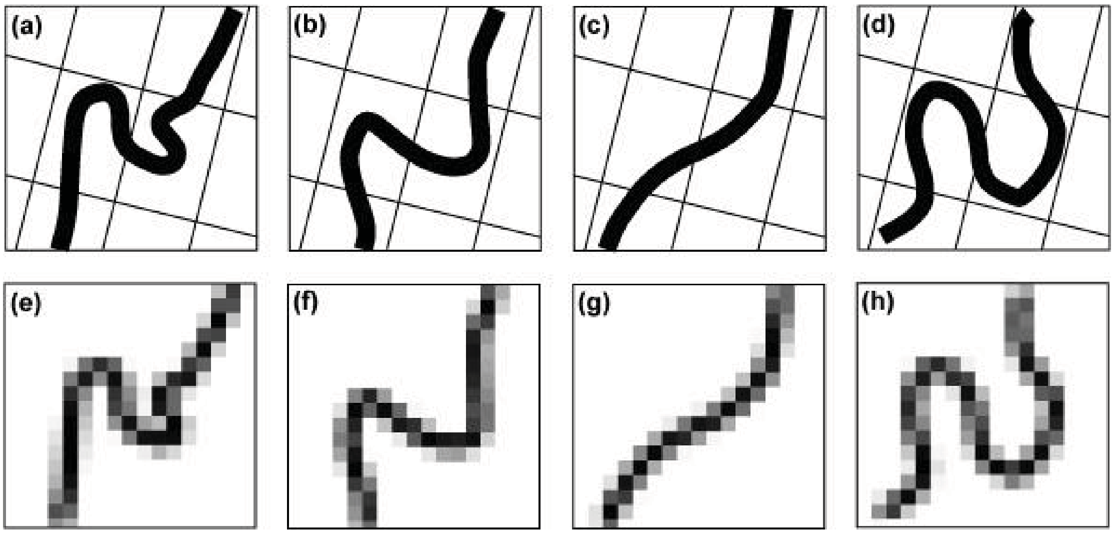

Figure 2: (a-d) Four possible interpretations of a channel morphology based on a coarse 2D seismic grid. (e-h) Schematic illustrations of how each of the interpretations in (a-d) would appear in a timeslice from a laterally continuous, binned 3D seismic volume. This demonstrates that 3D seismic data has the potential to distinguish between possible alternatives.

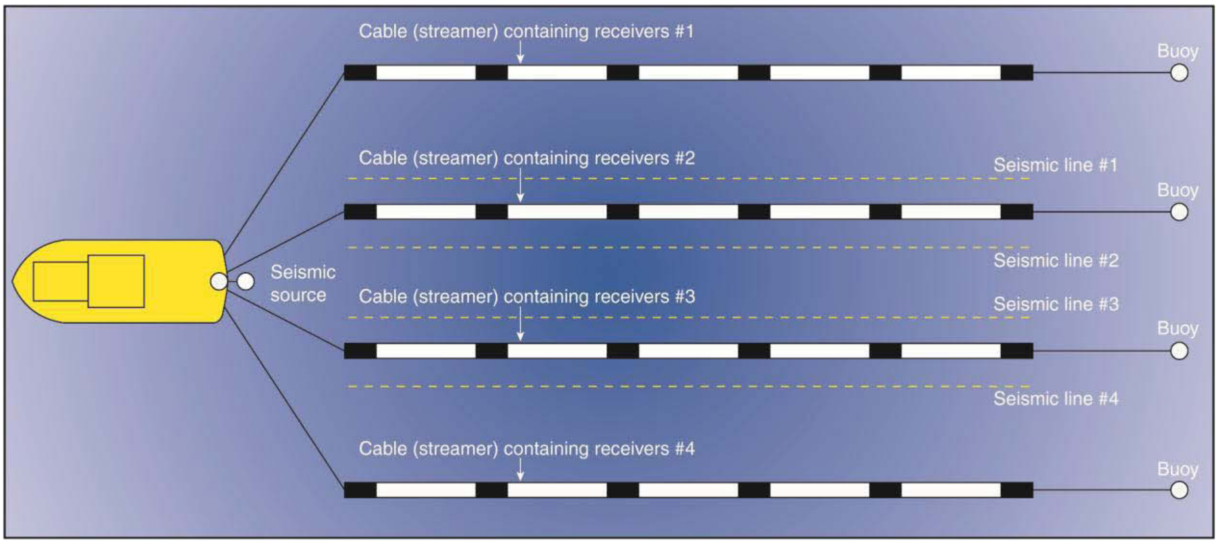

Figure 3: Typical 3D marine seismic reflection acquisition.

In contrast, 3D reflection seismic data involves the towing of multiple streamers which support the rapid collection of a series of closely spaced lines. The survey configuration provides significant advantages. Seismic response is correctly positioned in space and, in the case of data acquired for hydrocarbon exploration, is "binned" within data volumes with a resolution of 12.5m x 12.5m x 4 milliseconds, or multiples thereof. Once treated in this manner a feature can be mapped from bin to bin, removing the potential errors involved in the interpretation of 2D data (Figure 3 (e-h). Moreover, instead of relying on vertical profiles, the volume can be sliced in any direction. Of particular importance to the investigation of relatively shallow, and flat, landscape features is the ability to produce a horizontal slice (timeslice) through the data as this can, in many cases, be interpreted as a map showing a range of sedimentary features. The interpretation of 3D seismic data has improved significantly in recent years due to the development of a range of new techniques originally designed to improve geological interpretation associated with hydrocarbon exploration and production. Once a stratigraphic marker of interest has been identified, it can be mapped across the 3D seismic volume to produce a horizon that may have a geomorphological or chrono-stratigraphic value and, in some cases, the output can approximate the original land surface itself.

The value of such data for the interpretation and analysis of inundated landscapes and modeling past settlement or land use should be clear.

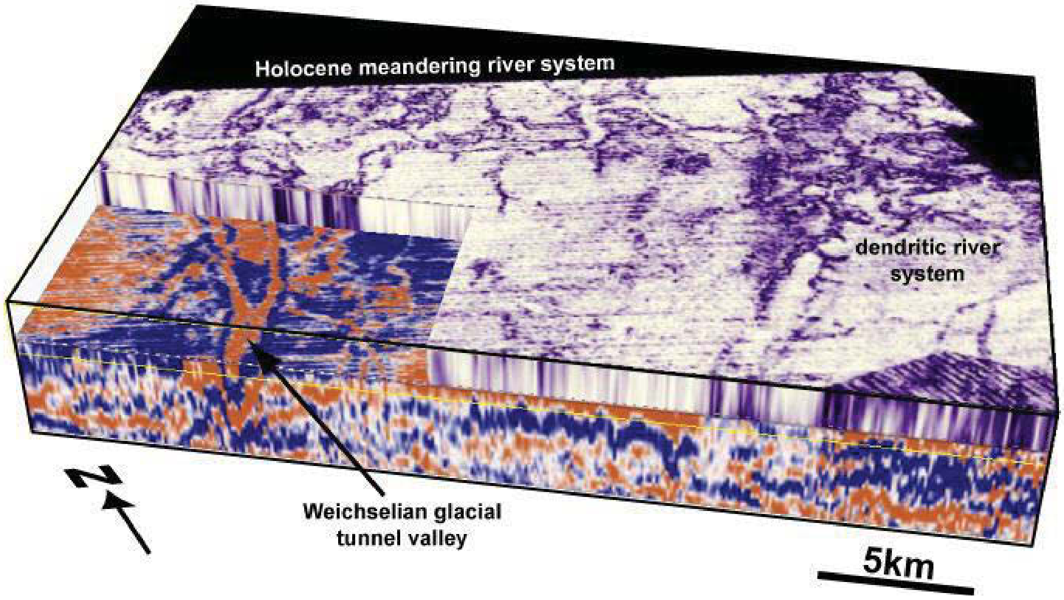

Figure 4: A cube of conventional 3D data with a section removed to demonstrate the ability to slice the data in the horizontal and vertical dimensions and to reveal landscapes of differing age.

Another advance in 3D seismic interpretation has been the development of opacity rendering techniques (Kidd 1999). Following conversion of conventional 3D seismic data into a voxel (3D pixel) volume, each voxel contains information from the original portion of the 3D seismic volume that it occupies together with an additional user-defined variable that controls its opacity. The opacity of individual voxels can then be varied as a function of their seismic amplitude (or any other attribute), allowing the user to examine only those voxels that fall within the particular amplitude (or attribute) range of interest. By using appropriate opacity filters it is possible to image the depositional systems such as buried fluvial channels. This exploits seismic characteristics, which are in part lithologically dependent, and different from the surrounding materials, thus permitting the surrounding strata to be made transparent whilst preserving all but the smallest channels as opaque features (Fitch et al. 2005). In archaeological terms such processing also provides further insight into the stratigraphic relationship of features identified and, through their volume and sedimentary characteristics, the opportunity to assess whether such features have the potential for preservation of archaeological or environmental data.

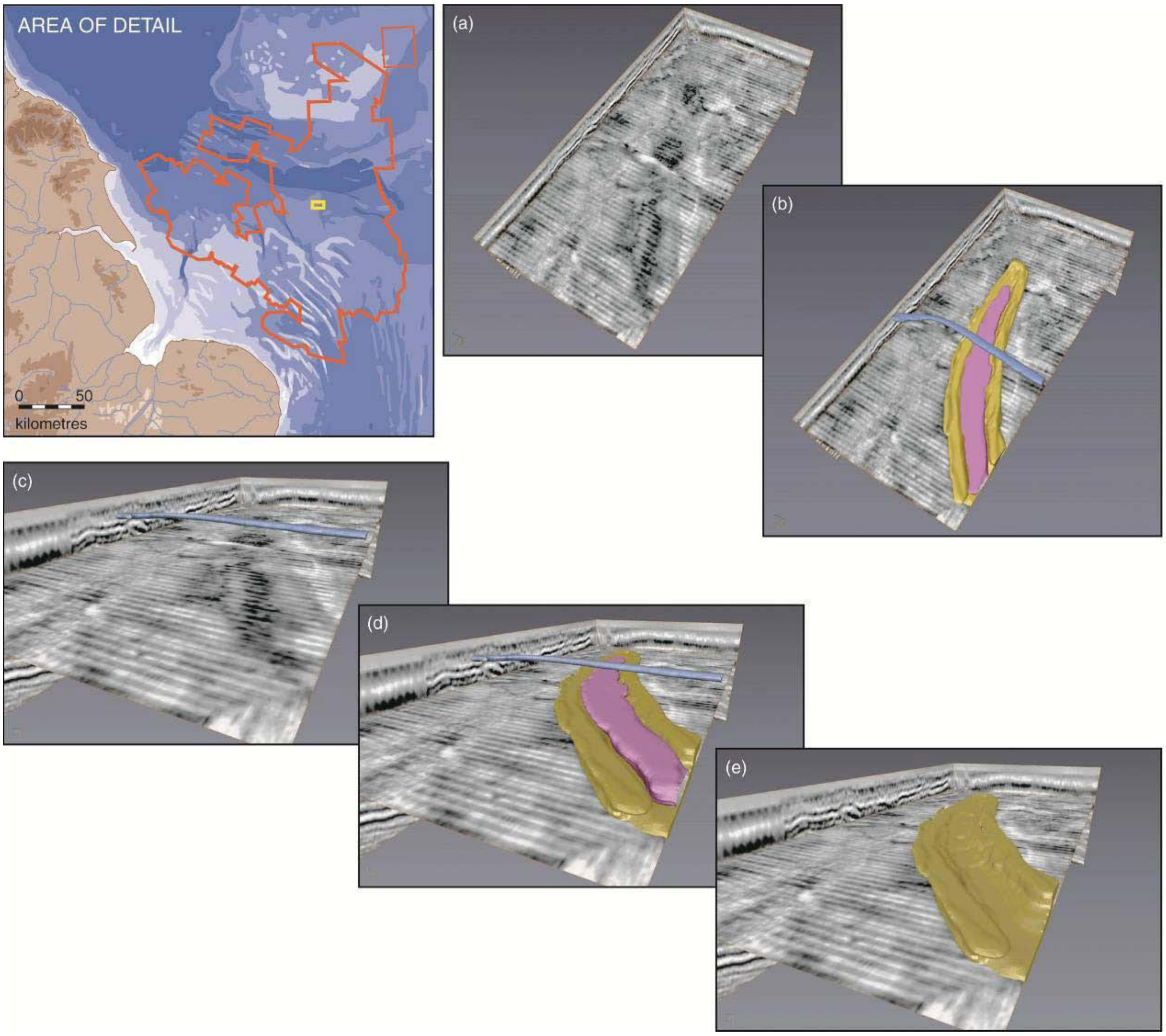

Figure 5: A volume model of the data illustrated in Figure 4. A Holocene river channel (blue) overlies an older tunnel valley (gold and infilling sediments in purple).

Generally, the ideal dataset for the investigation of submerged prehistoric landscapes within the region would be high-resolution (>100Hz) 3D seismic data with appropriate borehole control. Such a dataset would provide high (metre or less) vertical and lateral resolution and a laterally continuous coverage. Unfortunately, such systems involve slower survey rates, higher costs and do not usually provide the extensive output required to explore landscapes at a supranational scale. Commercial 3D seismic datasets, which possess a significantly coarser resolution may appear to be less suitable for archaeological exploration but even these can provide maps containing important information from shallow deposits. Consequently, even with a bin spacing of 50m, the areal coverage of such datasets and published outputs demonstrate that these data have the potential to provide an extensive reconnaissance tool for the investigation of submerged landscapes.

Developments in petroleum industry data collection suggest that the current situation can be further improved through the development of extensive high definition 3D (HD3D) survey which offers greatly improved vertical resolution and feature definition (Figure 6; Long 2003). This has been achieved by improved technology that supports acquisition of data through a denser 3D spatial sampling grid and improved frequency bandwidth recovery than is available to traditional 3D seismic reflection surveys. Although not widely available at present, archaeological research undertaken at the University of Birmingham on HD3D data from the Gulf suggests that this data may be eminently suitable for the exploration of areas where noise or water depth issues occur (Cuttler et al.

2010, Mueller et al. 2006). The acquisition of such data is becoming more frequent within the mineral sector and as access to such data is improved then future archaeological applications are likely to result in finer resolution, broad area, palaeolandscape investigations.

Figure 6: Shallow time slice from HD3D data in Qatar. The resolution of the complex meandering channel systems is outstanding, and signal-to-noise quality is a step improvement over historical seismic data in such shallow waters. Data courtesy of Maersk Petroleum (Qatar) Ltd.

Where HD3D data datasets do not exist and there is a requirement for accurate survey and modelling of submerged landscapes, or in areas where traditional 3D data is not universally available, a fusion of both 3D and 2D seismic datasets may be appropriate. This approach has been utilised for the purposes of petroleum exploration, and has more recently been applied to archaeological landscape survey in Liverpool Bay and in prospection off the Humber estuary (Fitch et al. 2010; Bennike et al. 2004; Novak & Bjorck 2002). Such an approach combines the strengths of both datasets and has a number of applications. The interpreted results of extensive, low-resolution data can be used as a guide to implementing high-resolution survey to explore areas identified as being of potential interest. Alternately, where coincident 2D data sets can be identified, these can be acquired to add fine detail to mapping derived from coarser 3D data sets (Figure 7). Although lacking the full and comprehensive 3D-framework associated with HD3D data the fusion of 2D and 3D seismic data has the benefit of being able to combine existing legacy datasets to produce a high definition interpretation, thus maximising the information value of existing data assets and, potentially, reducing the need for re-survey.

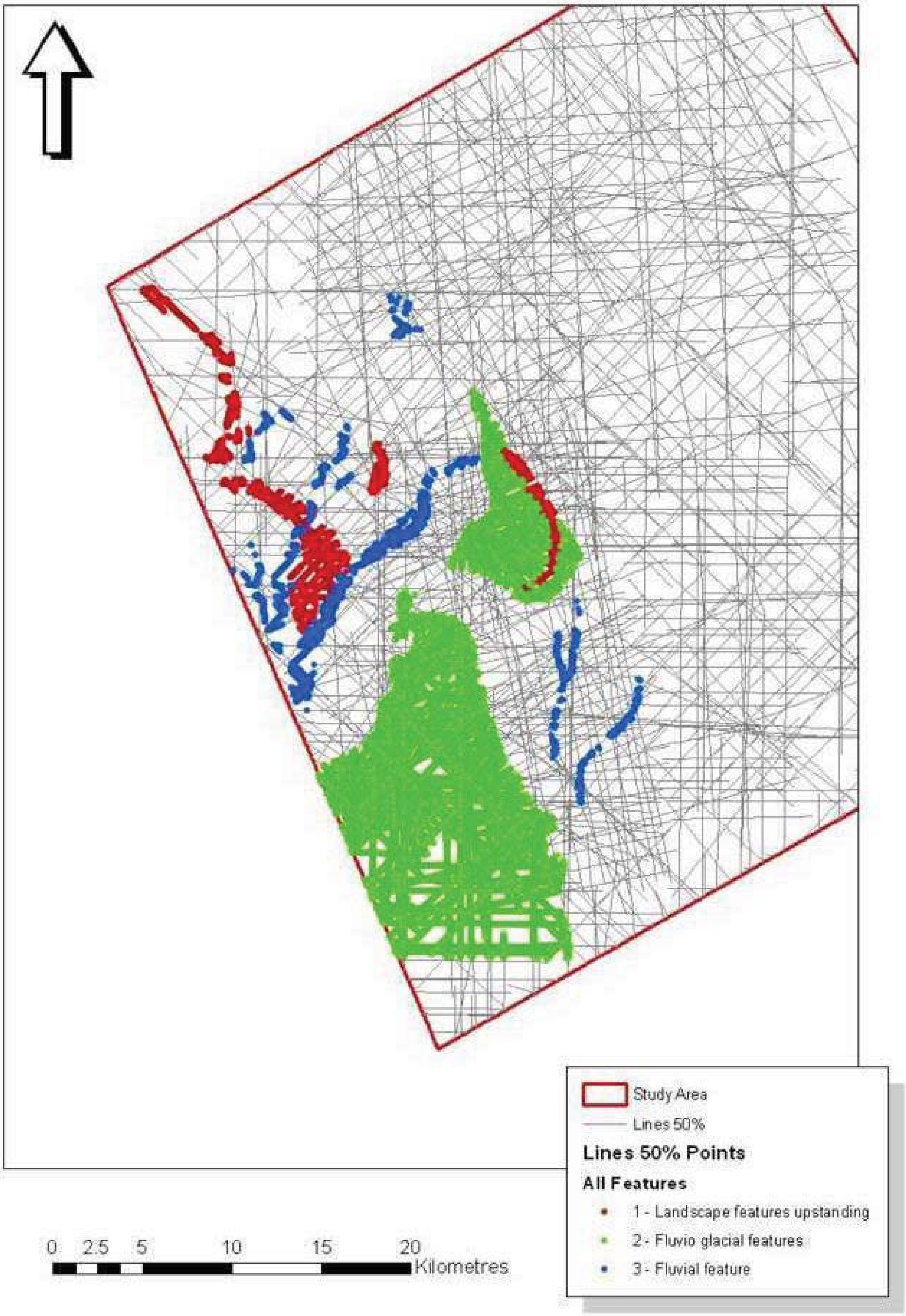

Figure 7: Data fusion: the coincidence of 2D lines with features identified within 3D data sets in Liverpool Bay (Fitch et al. 2009).

The challenges of working in a marine environment where the archaeological resource is essentially unknown and largely inaccessible are immense and should not be undertaken lightly either in terms of cost, technological investment and skill requirments. However, as David Clarke (1936) said about the marine potential of Holocene marine landscapes in the southern North Sea " It would be possible to take comfort from the fact that such cultures might not have existed were it not eminently probable that they not only existed, but flourished". We can be equally confident that, not only will such information on early landscapes be preserved within marine contexts, there is existing evidence that remote sensing surveys can provide a wider landscape context for existing or suspected archaeology (Figure 8).

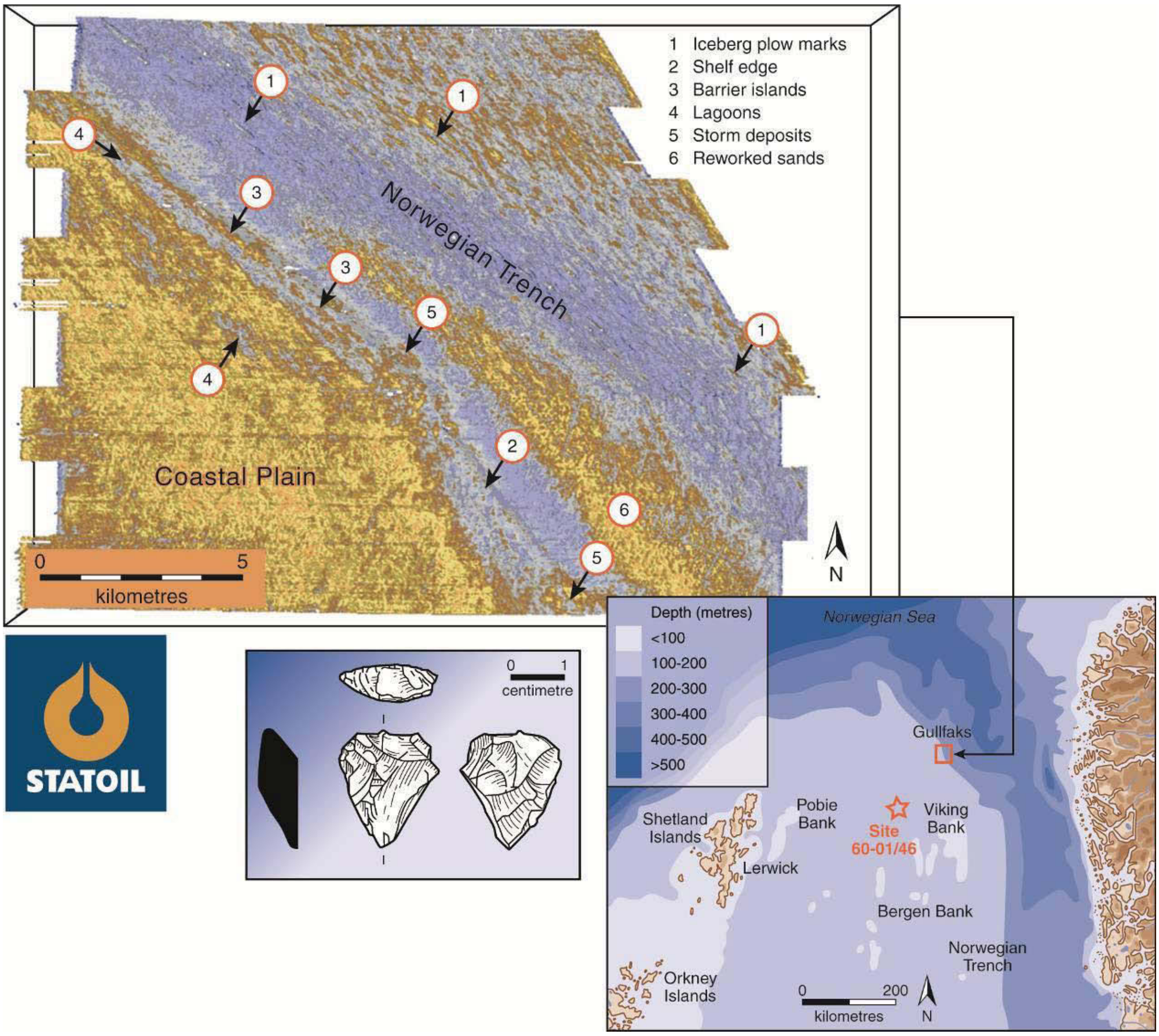

Figure 8: Lithic find from coring on the Viking Banks and seismic interpretation of the Later Palaeolithic coastline of Europe (Long et al. 1986 and Statoil).

In such circumstances, remote sensing is always likely to be our primary guide and, in one form or another, may well be the only way to investigate the majority of the inundated landscapes surrounding our coasts. However, it is apparent that there is not one data source or methodology that will satisfy the requirements of all archaeologists or heritage managers. Consequently, the methodologies and technologies chosen will always depend upon the nature of the archaeological questions being posed. Some projects, including those which seek detailed sediment sampling, proxy or even direct evidence for settlement or land use, may well require high resolution survey and demand the acquisition of new data in areas which have not previously attracted survey. In other circumstances, the availability of the extraordinarily large, pre-existing data sets that have been acquired around our coasts, and which could never have been provided for archaeological purposes alone, have the capacity to inform and guide the development of research agendas in their own right. In the case of research involving supranational behavioural or settlement modelling, the relatively coarse data sets which were acquired for non-archaeological purposes, may well be adequate and, along with improved data on sea level rise and geomorphological change, have the potential to provide dramatic, new insights into landscapes which may be key to our regional models but which we may never be able to explore directly.

References

Bennike, O., Jensen, J. B., Lemke, W., Kuijpers, A. & Lomholt. S. 2004: Late- and postglacial history of the Great Belt, Denmark. *Boreas* 33:18–33.

Bulat, J. 2005. Some considerations on the interpretation of seabed images based on commercial 3D seismic in the Faroe-Shetland Channel. *Basin Research* 17:21-42.

Clark, J. G. D. 1936. *The Mesolithic Settlement of Europe*. Cambridge: Cambridge University Press.

Fitch, S., Thomson, K. & Gaffney, V. L. 2005. Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research* 64:185-196.

Cuttler R., Fitch S. & Al-Naimi F.A. 2010. Considering the „Terra Incognita' and the implications for the Cultural Resource Management of the Arabian Gulf Palaeolandscape. In Potts D., Al Naboodah H. & Hellyer P. (Eds.) *Archaeology of the United Arab Emirates: Proceedings of the Second Conference on the Archaeology of the UAE*. London: Trident Press

Fitch S., Gaffney V., and Ramsay E. 2010. West Coast Palaeolandscape Pilot Project. Unpublished manuscript. Aggregates levy Sustainability Fund/English Heritage

Gaffney V., Thomson K. and Fitch S. (Eds.) 2007. *Mapping Doggerland: The Mesolithic Landscapes of the Southern North Sea*. Archaeopress. Oxford.

Gaffney V., Fitch S. & Smith D. 2009. *Europe's Lost World: the rediscovery of Doggerland*. CBA Research Report 160. York: Council for British Archaeology

Kidd, G. D. 1999. Fundamentals of 3D seismic volume visualization. *The Leading Edge* 18:702-709.

Long, A. 2003. Removing seismic noise and increasing resolution in the East Java Sea: High Density 3D acquisition and processing. *PetroMin* 29(8):26-29.

Long, D., Wickham-Jones, C. R., and Ruckley, N. A. 1986. A flint artefact from the northern North Sea. In D. Roe (ed.) *Studies in the Upper Palaeolithic of Britain and North Western Europe*. BAR International Series. 296**:**55-62.

Mueller C, Luebke H, Woelz S., Jokisch T., Wendt G & Rabbel W. 2006. Marine 3-D seismic investigation of a late Ertebølle settlement in Wismar Bay (SEAMAP-3D case study). *Geophysical Research Abstracts* 8:08447, SRef-ID: 1607-7962/gra/EGU06-A-08447

Novak, B & Bjorck, S. 2002: Late Pleistocene–early Holocene fluvial facies and depositional processes in the Fehmarn Belt, between Germany and Denmark, revealed by high-resolution seismic and lithofacies analysis. *Sedimentology* 49:451-465

Praeg, D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin - high resolution from low frequencies. *Journal of Applied Geophysics* 53:273-298.

Salomonsen, I., & Jensen, K. A. 1994. Quaternary erosional surfaces in the Danish North Sea. *Boreas* 23:244-253.

Velegrakis, A. F., Dix, J. K. and Collins, M. B. 1999. Late Quaternary evolution of the upper reaches of the Solent River, Southern England, based upon marine geophysical evidence. *Journal of the Geological Society, London*. 156:73-87.