3D seismic reflection data, associated technologies and the development of the project methodology.

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Abstract
This paper discusses the issues related to the design of the project methodology. It briefly assesses the possible data types available before providing a summary of the marine seismic reflection acquisition, resolution and the relative merits of 2D versus 3D seismic data. It demonstrates that existing 3D seismic reflection data from the Southern North Sea, acquired for hydrocarbon exploration, provides the ideal tool for regional mapping of submerged Holocene/Mesolithic landscapes.

Key Words
Seismic reflection, seismic resolution, 2D seismic, 3D seismic, seismic attributes, seismic interpretation, seismic visualisation.

Introduction

A variety of methods and datasets were potentially available to project. However, as the choice of methods, and hence data types, critically controls the volume and quality of the results an optimal approach needed to be developed. A crucial consideration was the need to minimise the time involved in the analysis, and hence the expense of the project, whilst at the same time maximising the spatial coverage and detail. Consequently, the available technologies, the costs involved in acquiring new data and the possibilities for using existing data needed to be evaluated when the planning the project.

The Southern North Sea contains an extensive collection of data including seabed samples, shallow core, bathymetry data and seismic reflection profiles collected for the investigation of near seabed features or deeper hydrocarbon exploration. This suggested that the project could potentially achieve its aims by exploiting existing data with the future acquisition of bespoke datasets being considered, based on the project results. The existing datasets from the Southern North Sea were acquired for a variety of purposes and consequently have differing strengths and weaknesses. Seabed samples and shallow coring can provide chronological, sedimentological and environmental data. However, such data provides a poor spatial framework. Although high resolution bathymetry data can provide excellent images of the seabed topography, and hence detailed images of Holocene/Mesolithic features that have a bathymetric expression, many of the important geomorphological features are at least partially buried in the Southern North Sea. Consequently, there was a need for regionally extensive datasets that have the capability to image below the seabed. The only existing datasets within the Southern North Sea that could meet these requirements were seismic reflection datasets as these would permit the generation of region maps for buried Holocene landscape features. These datasets would then provide the framework into which data from shallow boreholes, seabed samples and bathymetry could be integrated.

Marine seismic acquisition is undertaken for a variety of purposes, with varying data densities, coverage, depths of penetration and resolution. Consequently, there was choice between differing seismic reflection data types, each being acquired for specific purposes that may not have been compatible with the project requirements. This paper will discuss these crucial parameters for differing seismic reflection data types and how these considerations influenced the project methodology.

Seismic reflection method and resolution.

Seismic reflection surveying involves the transmission of acoustic energy into the subsurface and recording the energy reflected from acoustic impendence contrasts to receivers. The reflections produced at acoustic impendence contrasts are predominantly the product of changes in lithology with the impendence contrast, or reflection coefficient (The ratio of amplitude of the reflected wave to the incident wave, or how much energy is reflected.), given by the equation:

$$R = (\rho_2 V_2 - \rho_1 V_1)/ (\rho_2 V_2 + \rho_1 V_1)$$

where R = reflection coefficient
ρ_1 = density of medium 1
ρ_2 = density of medium 2
V_1 = velocity of medium 1
V_2 = velocity of medium 2

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 (Klemperer and Hobbs, 1991), hydrocarbon exploration (Bally, 1987) and near seabed sediment structure (e.g. Salomonsen and Jensen, 1994; Velegrakis and Dix, 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 seismic reflection data types available for the investigation of submerged, and partially buried beneath more recent sediments, Holocene/Mesolithic geomorphic features within the Southern North Sea needs to be assessed.

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. In this case several shot-receiver pairs are of the correct geometry to collect acoustic energy reflected from the same point. These reflections can then be summed in order to increase the signal-to-noise ratio of the seismic profile.

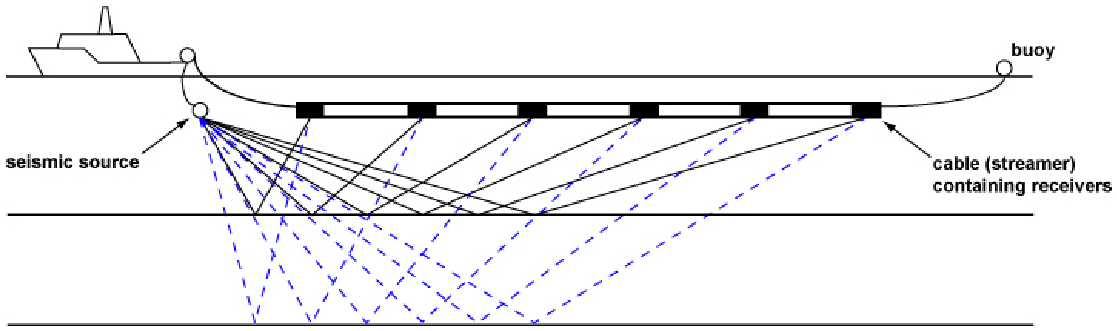

Figure 1 Typical marine seismic reflection acquisition. The vessel travels through the water and regularly fires the seismic source. The sound wave travel through the water column (and underlying sediments) and is partially reflected at acoustic impendence contrasts. Receivers within the long towed cable astern of the vessel detect the reflected wave, which is then transmitted to the vessel and recorded.

The characteristics of the seismic energy source are intimately linked to the required resolution and depth of penetration. The vertical resolution of seismic reflection data requires a minimum separation between two interfaces that will give rise to two separate reflections. At separations of less than ¼λ the reflections from the two acoustic impedance contrasts constructively interfere with the maximum amplitude occurring at ¼λ, known as the tuning thickness (Figure 2). However, it is not until ½λ that the two reflections area separable (Figure 2). Consequently, the vertical resolution of seismic reflection data can be defined as either the minimum resolvable (¼λ; Figure 3) or the minimum separable (½λ; Figure 3). As the vertical resolution is dependent upon the wavelength it is therefore dependent on the velocity of the medium and the frequency of the seismic source/reflected wave. Ideally, a high frequency source (>100Hz) would be used in all circumstances. However, as the Earth progressively dampens high frequency seismic signals with increasing depth, the choice of seismic source needs to be chosen with consideration to the required depth of penetration. The dampening effect of the top few hundred metres of overburden is relatively small and consequently seismic sources with frequencies in excess of 100Hz can be employed. In contrast, 2D and 3D seismic data acquired for hydrocarbon exploration need to image to depths of several kilometres and consequently employ sources with frequencies of less than 100Hz. This, combined with the increasing velocity with depth, results in a significantly higher vertical resolution for 2D seismic data specifically acquired for the investigation of shallow geology (<1km) compared to standard 2D or 3D seismic data required for hydrocarbon exploration. This is demonstrated in Figure 4 where a high frequency 2D seismic line specifically designed to image Holocene and Quaternary features is compared with a line from exactly the same position extracted from a 3D seismic dataset acquired for hydrocarbon exploration. The high-resolution line (Figure 4a) shows a channel and its complex infill pattern. In contrast, the low-resolution 3D seismic line (Figure 4b) is unable to image the channel.

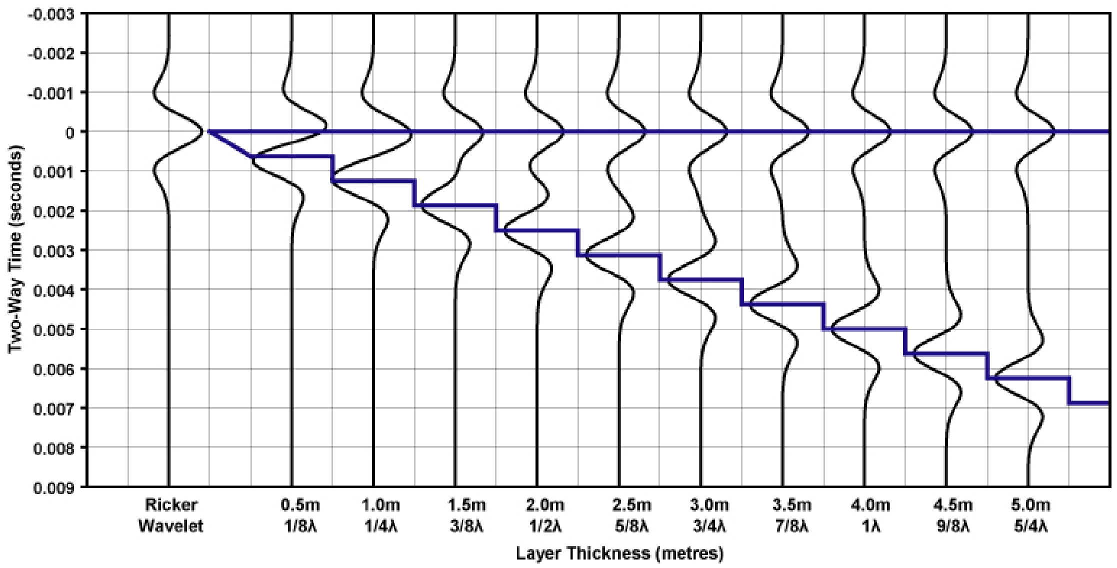

Figure 2 Seismic resolution of a layer of varying thickness. The blue lines show the top and base of a layer. Using a 400Hz Ricker wavelet, and assuming a sediment velocity of 1600ms^{-1}, the reflections from the top and base can be shown to constructively interfere at thicknesses less than ¼λ (1 metre) with the maximum amplitude at ¼λ. Furthermore, the top and the base of the layer do not perfectly align with peak and troughs. At thicknesses of ½λ (2 metres) and greater the top and the base of the layer are separable with peak and troughs aligning perfectly with the position of the top and base respectively.

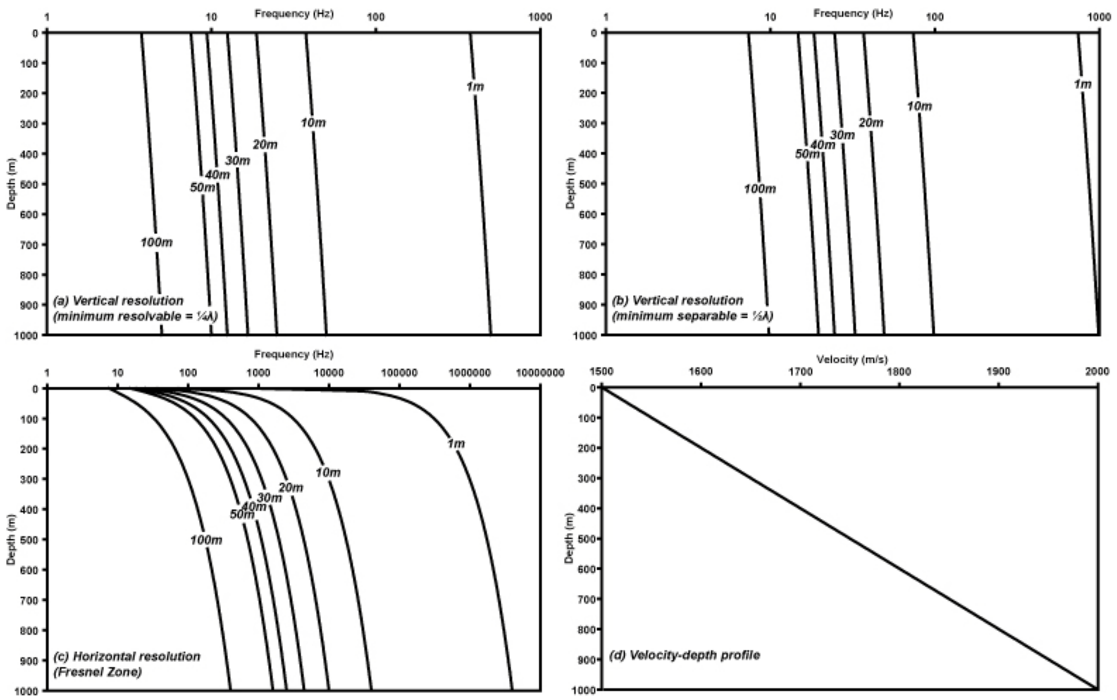

Figure 3 Plots of seismic resolution as a function of burial depth and frequency. (a) The minimum resolvable vertical resolution. (b) The minimum separable vertical resolution. (c) The horizontal resolution of unmigrated seismic data. (d) The assumed velocity-depth structure.

The lateral resolution of seismic reflection data is dependent on the fact that seismic energy travels through the subsurface and encounters the reflecting surfaces over discrete areas. The energy travels as wave fronts and the region on the reflector where the seismic energy is reflected constructively is known as the Fresnel Zone (Sherrif, 1977). Lateral resolution is determined by the radius of the Fresnel Zone, which itself depends on the wavelength of the acoustic pulse and the depth of the reflector. Thus in non-migrated seismic data, lateral resolution is dependent on the frequency of the seismic source, the interval velocity and on the travel time to the reflector. As with the vertical resolution, this implies that high frequency seismic reflection data will provide a significantly higher lateral resolution compared to lower frequency data collected for hydrocarbon exploration (Figure 3). However, the procedure of migrating seismic data, which ensures reflected energy is correctly positioned within the subsurface, considerably enhances resolution. Thus for migrated data, lateral resolution depends on trace spacing, the length of the migration operator, time/depth of the reflector and the bandwidth of the data. If completely successful then the lateral resolution of the high frequency seismic section shown in Figure 4(a) would be approximately 12m compared to 50m for the low-resolution 3D seismic line (Figure 4b).

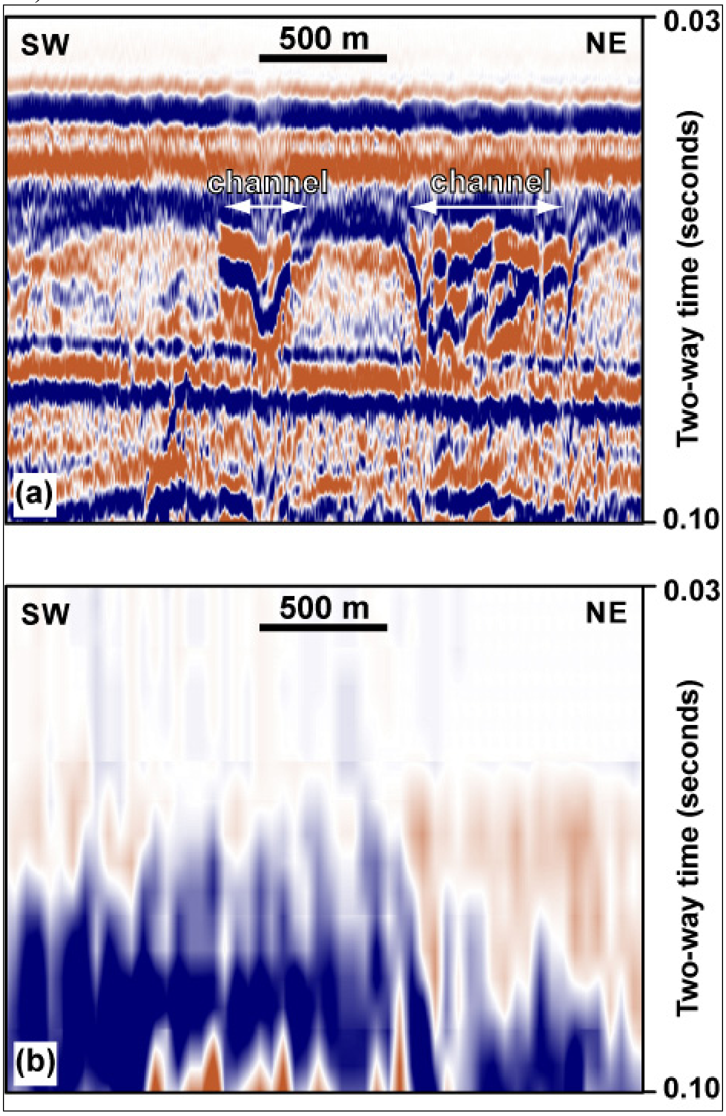

Figure 4 A comparison between (a) high frequency 2D seismic reflection line and (b) low frequency 3D seismic line from the same location. Note that higher frequencies yield greater vertical detail.

2D versus 3D seismic acquisition and interpretation.
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 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. This aliasing means that the location of a feature cannot be accurately constrained as the spacing between lines is too wide correct this error. Secondly, the spacing between lines is sufficiently wide that it can be difficult to map the position of a morphological feature across the region of interest. For example, Figure 5 demonstrates how wide line spacing can lead to several equally valid interpretations.

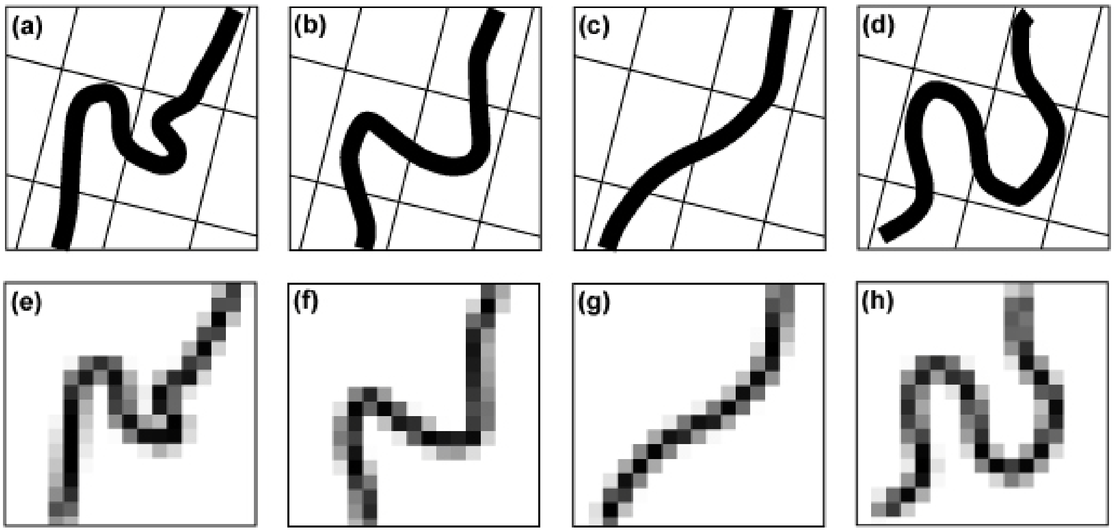

Figure 5 (a-d) Four possible interpretations of a channel morphology based on a coarse 2D seismic grid. Each interpretation is equally valid. (e-h) Schematic illustrations of how each of the interpretations shown in a-d would appear on a timeslice from a laterally continuous, binned 3D seismic volume. This demonstrates that 3D seismic data has the potential to distinguish between the possible alternatives.

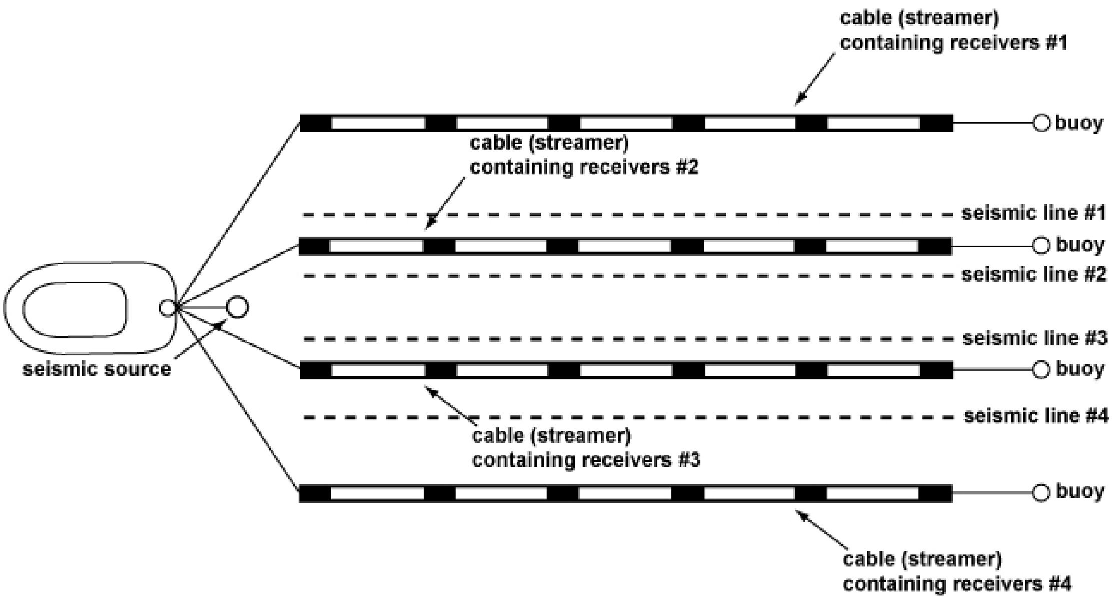

Figure 6 Typical 3D marine seismic reflection acquisition. The vessel travels through the water and regularly fires the seismic source. The sound wave travel through the water column (and underlying sediments) and is partially reflected at acoustic impendence contrasts. Receivers within the towed cables astern of the vessel detect the reflected wave, which is then transmitted to the vessel and recorded. In contrast to Figure 1, 3D acquisition involved multiple towed cables with each cable being capable of producing a seismic profile.

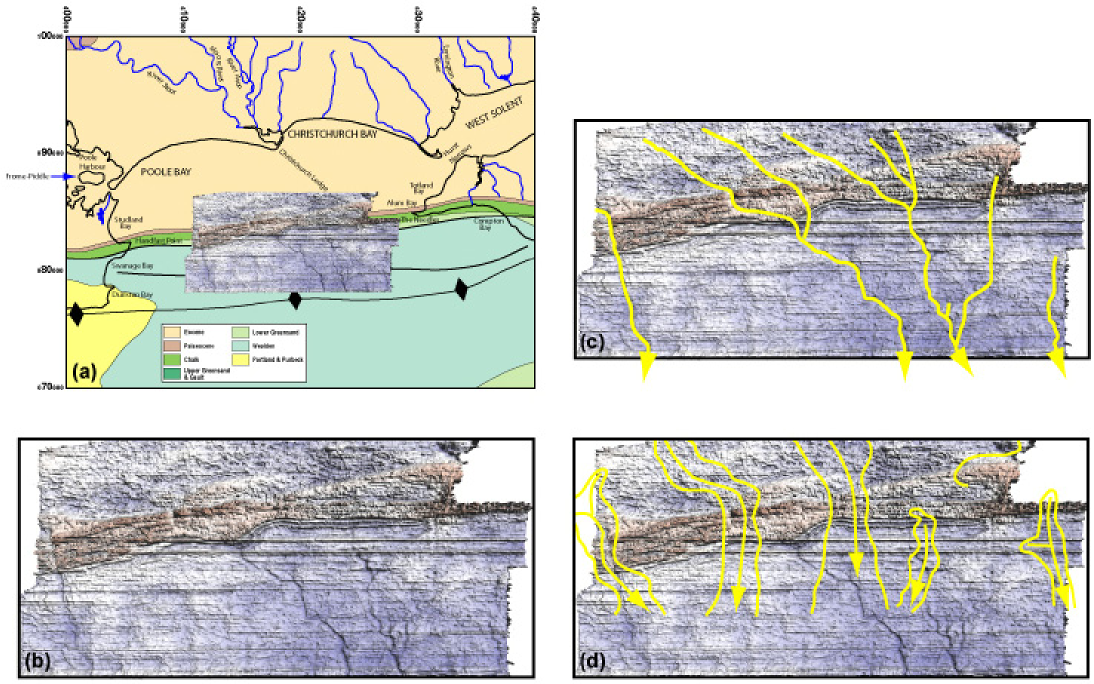

Figure 7 (a) Geological map of Poole and Christchurch bays with the artificially illuminated plan view of the seabed reflector. (b) Artificially illuminated plan view of the seabed reflector. (c) Artificially illuminated plan view of the seabed reflector with palaeo-channels as mapped using 3D seismic. (d) Artificially illuminated plan view of the seabed reflector with palaeo-channels as mapped using 2D seismic data Velegrakis et al. (1999). Note the poorly correlation between the 2D interpretation and the actual channel locations.

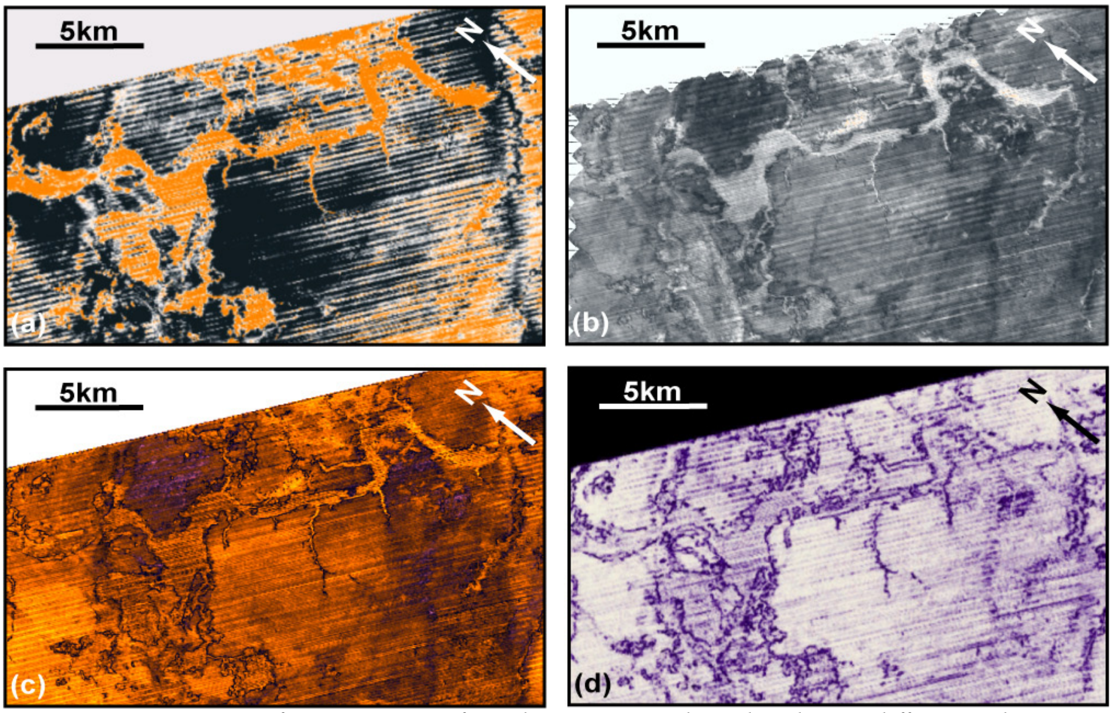

Figure 8 A comparison of seismic images from the Dogger Bank produced using different techniques. (a) Simple seismic amplitude timeslice revealing some Holocene depositional features (channels). (b) RMS amplitude extraction for the top 200ms of the data. (c) Opacity rendering of the same seismic volume from as (b). Note that both the RMS extraction and the manipulation of the opacity allows some improvement in channel definition. (d) Seismic coherence (semblance) timeslice at the same level as (a). Note that coherence provides some additional detail of the channels.

In contrast, 3D reflection seismic data involves the towing of multiple streamers (Figure 6) which allows the rapid collection of multiple closely spaced lines. The survey configuration provides significant advantages as it is generally involves multifold collection, that is containing several reflections from the same subsurface location, and allows reflected energy to be correctly positioned in space thus eliminating the potential positioning errors associated with 2D seismic data. This is achieved through the conversion into a binned dataset with, in the case of data acquired for hydrocarbon exploration, the bin spacing being 12.5m x 12.5m x 4 milliseconds, or multiples thereof. Each bin is then populated by those reflections that originated from within the bin space. Once binned the data format provides additional benefits. Firstly a laterally continuous binned data volume means that a geomorphological feature can be mapped from bin to bin, removing the potential errors involved in the interpretation of 2D data (Figures 5 and 7). However, 3D seismic is also more versatile than 2D data as it can be interrogated in a number of ways. 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, Holocene features is the ability to produce a horizontal slice (timeslice) through the data as this can, in many cases, be interpreted as a geological map showing a range of sedimentary features and facies patterns (Figure 8; Fitch et al., 2004).

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. This can then be examined using a variety of attributes (e.g. depth, seismic amplitude, dip, azimuth) with each attribute having the potential to reveal different characteristics of the feature of interest (Posamentier, 2005). However, simply applying artificial illumination from a number of directions can prove highly effective at identifying subtle geomorphological features.

Seismic attributes can also play a crucial role in the interpretation of 3D seismic data. Extracting RMS amplitude (root-mean-square) over a two-way time interval, defined by two mapped horizons or two timeslices, is commonly employed to differentiate zones of different seismic amplitude within a seismic volume (e.g. Den Hartog Jager et al., 1993). As seismic amplitude is a function of density and/or velocity contrasts it is often closely related to the depositional facies (Figure 8). Further enhancement of the seismic slices (both vertical or horizontal) and mapped horizons can be achieved through the generation a coherence (or semblance) seismic volume. The coherence cube (Bahorich and Farmer, 1995) calculates localised waveform similarity in both inline and crossline directions and estimates of three-dimensional seismic coherence are obtained. Small regions within the seismic volume containing stratigraphic anomalies such as channels have a different seismic character compared to the corresponding regions of neighbouring traces. This results in a sharp discontinuity in local trace-to-trace coherence and allows the rapid identification of stratigraphic features (Figure 8; Bahorich and Farmer, 1995).

Another advance in 3D seismic interpretation has been the development of opacity rendering techniques Kidd (1999). The technique converts conventional 3D seismic data into a voxel volume, with each voxel containing the 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 seismic 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 rock to be made transparent whilst preserving all but the smallest channels as opaque features (Figure 8; Fitch et al., 2004).

Interpretation strategy for the Southern North Sea.

The above discussion demonstrates that the ideal dataset for the investigation of submerged Holocene/Mesolithic landscapes within the region would be a high resolution (>100Hz) 3D seismic data with appropriate borehole control. Such a dataset would provide high (metre or less) vertical and lateral resolution, the ability to apply the latest advances in seismic attributes and visualisation to aid interpretation and a laterally continuous data coverage, thus removing the need to interpret the location of a feature between data points. Unfortunately, high-resolution 3D seismic surveying equipment, such as the 3D CHIRP system developed by the National Oceanography Centre, Southampton (Gutowski, 2005), is a recent development and consequently such data is extremely rare. Furthermore, such systems currently utilise small vessels that are not suitable for deployment beyond the immediate coastal waters. However, it is the high resolution of the system that is the most significant handicap. High-resolution seismic acquisition involves much slower surveying rates and thus higher costs. For example, the 3D CHIRP system described by Gutowski (2005) is capable of surveying approximately 0.02km^2 per day. This contrasts with the lower resolution 3D seismic data acquired for hydrocarbon exploration, which although it involves large, expensive and custom-built vessels, can survey 40km^2 a day at a cost of $5000 per square kilometre (Bacon et al., 2003).

Although high-resolution 3D seismic data is expensive to acquire and not readily available it is interesting to consider the advantages of using existing 3D seismic data acquired for hydrocarbon exploration. The frequency spectra for the top 200ms (the likely depth/two-way time range of interest) of the dataset used in this study has 98.7% of the frequency content in the 3-72Hz range with a mean frequency of 14.7Hz. Consequently, a mean frequency of 14.7Hz provides a vertical resolution of 27m although the higher frequency components suggest that a vertical resolution of 10m or less may be possible. The limit of horizontal resolution for unmigrated seismic data ,the Fresnel Zone (Sherrif, 1977), for the mean frequency of 14.7Hz would provide a Freznel Zone width of 66m. However, this can be considered an extremely conservative estimate as the higher frequency components suggest lateral resolutions of around 30m may be possible (Emery and Myers, 1996). In addition, as migration of the seismic data considerably enhances lateral resolution with the limit being dependent upon trace spacing, length of the migration operator and the bandwidth of the data. Consequently, the lateral resolution of the top 200ms of the migrated dataset used in this study may actually approach the line spacing of 50m.

Although these parameters may suggest that the commercial 3D seismic datasets acquired for hydrocarbon exploration are not suitable for the exploration of Holocene/Mesolithic landscapes in the Southern North Sea the reverse is actually true. For example, Figure 7 is an artificially illuminated map of the seabed reflector from Poole and Christchurch bays, English Channel mapped using commercial 3D seismic data from over the Wytch Farm oilfield. The map shows a number of North-South trending channels that do not possess a current bathymetric expression. Instead, Velegrakis et al. (1999) demonstrated, using 2D seismic data, that these channels are completely infilled and are sub-seabed features. Consequently, Figure 7 demonstrates that the vertical resolution of approximately 10m results in a mean response from both the seabed and the acoustic impedance contrasts from several metres below it (c.f. Bulat, 2005). This implies that mapping the seabed, or any other near seabed reflector, can provide maps containing information from several metres of Holocene/Mesolithic strata. Furthermore, a timeslice can be considered to also provide information from a stratigraphic interval several metres thick. Given a bin spacing of 50m, and an areal coverage of >20,000km^3, this suggests that timeslicing and mapping regionally significant reflectors has the potential to provide a regionally extensive reconnaissance tool for the investigation of Holocene/Mesolithic landscapes (Figures 8 and 9).

The above considerations therefore suggest that an alternative interpretation strategy could be employed for the investigation of Holocene/Mesolithic landscapes beneath the Southern North Sea. This approach was completely dependent on the donation of >20,000km^3 of commercial 3D seismic data by PGS Reservoir. This would provide an opportunity to rapidly develop a regional framework into which other, higher resolution datasets, could subsequently be integrated. The approach was:

1. To map regionally significant reflectors using the regional 3D seismic dataset.
2. To interpret these surfaces using artificial illumination and horizon attributes such as amplitude and dip to identify morphological features and the developmental chronology.
3. To generate seismic attributes for the regional 3D seismic dataset.
4. To sequentially timeslice these attribute volumes (e.g. amplitude, coherence, RMS amplitude) and to employ opacity rendering techniques to identify morphological features and the developmental chronology.
5. Integrate the above to develop a first order geomorphic model.
6. Use existing high resolution 2D seismic data and shallow borehole data to refine the geomorphic model, resolve interpretational and chronological ambiguities, and to provide palaeoenvironmental data.

This strategy provided several advantages. Firstly, it optimised the use of existing data thus reducing the cost of the project. More importantly, the speed of the project was significantly increased as the 3D seismic permitted the rapid development of a regional model and the identification of key localities for detailed work. These could be identified on the basis of the need for clarification or a recognition of their environmental importance.

Conclusions.

The key requirement for understanding the Mesolithic archaeological potential of the Southern North Sea is the development of a detailed regional landscape model. Given the vast area under consideration the traditional archaeological approach would suggest a requirement for the acquisition of a large bespoke geophysical survey of the area, with appropriate stratigraphic, sedimentological and environmental controls from cores. The expense, and logistical complexity, involved in such a survey would be prohibitive. Consequently, there existed a need to develop a regionally extensive and detailed landscape model utilising existing data. Fundamental to developing such a model would be access to regionally extensive seismic reflection datasets but given the range uses such data are acquired for the acquisition parameters vary considerably and hence have varying degrees of applicability to the study of Holocene/Mesolithic landscapes. Although traditional 2D high frequency, high resolution seismic reflection data have been the preferred dataset for the investigation of Holocene/Mesolithic geology and archaeology such datasets are limited in there use as regional mapping tools as they prone to spatial aliasing errors and require extrapolation of geomorphic feature between relatively widely spaced datapoints. Conversely, 3D seismic data acquired for hydrocarbon exploration have significantly lower resolution but complete spatial coverage. This removes the aliasing issues and also allows a range of techniques such as timeslicing, attribute analysis and seismic visualisation to be applied. These advantages permit the rapid development of a regional geomorphic model into which higher resolution seismic reflection data, bathymetry, seabed samples and shallow core can be integrated.

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