The new synergy between seismic reflection imaging and oceanography

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Abstract

The effects of variation in oceanic temperature and salinity on reflection seismic images became widely known to the hydrocarbon industry in 1993 following acquisition of large 3D seismic surveys in the Faroe-Shetland Channel. A decade later, it was shown convincingly that conventional reflection seismic data provide good quality images of oceanic thermohaline structure. Over the past five years, it has been established that seismic reflection surveying provides a tool to efficiently survey unprecedently large ocean volumes at high spatial resolution. We illustrate the processing stages required to produce oceanic images using seismic data from Rockall Trough, west of Ireland. When the cause of the seismic reflectivity is better understood, seismic images might eventually be used to measure spatial variation in oceanic mixing, which should significantly enhance our understanding of the climate system. The industry has the chance to help in mapping the ocean by facilitating access to legacy seismic data and by making the water layer of new seismic data available for academic research. Ability to predict spatial and temporal variation in oceanic temperature and currents, at little extra cost in comparison with seismic data acquisition, should also help the industry in field development and management.

Introduction

Hydrocarbon exploration has expanded into the deepwater frontier over the past two decades. The burgeoning deepwater seismic database acquired during this phase of exploration is now bringing benefits in a different area. When standard seismic processing techniques are targeted at the water layer, unexpected images can result that are currently making waves in the oceanography community (Figure 1). By providing a method to map detailed oceanic structure over unprecedentedly large volumes, the new synergy between oceanography and seismology promises to shed light on problems such as oceanic mixing, climate change, and continental slope stability. We first describe the history of the new synergy and then illustrate the processing stages required to produce seismic images of the ocean using an example from Rockall Trough, west of Ireland. Finally, we discuss the implications of the new images both for oceanography and for the hydrocarbon industry.

Acoustical oceanography

The effects of variations in oceanic temperature, salinity, and currents on reflection seismic images became widely known to the hydrocarbon industry in 1993, following acquisition of large 3D seismic data surveys in the Faroe-Shetland Channel. Differences in water layer travel time in excess of 20 ms at 3D swath boundaries were at first attributed to errors in positioning, since the water layer was initially assumed to have a fixed seismic velocity. It was soon realized that the travel time differences are caused by changes in the seismic velocity of seawater throughout acquisition, related to mixing of colder waters from north of Iceland with warmer southern waters carried by the Gulf Stream. Today, the variable water velocity problem is still a challenge both for 3D processing and particularly for 4D seismic monitoring in oilfield management (Barley, 1999; Bertrand and MacBeth, 2002). The problem was originally treated using a vertical static shift approach borrowed from processing of land-based seismic data. This approach solves and then corrects for variation in the average velocity of the water layer (Wombell, 1997; Xu and Pham, 2003). Tidal oscillation in water column thickness also contributes to variation in water layer travel time, and the static shift approach can be used to correct for tidal level and seismic velocity variation simultaneously (Lacombe et al., 2006). Mackay et al. (2003) discussed the possibility of measuring seismic water velocities directly using semblance analysis and inversion of direct arrivals, but concluded that these methods are too cumbersome to routinely use on large deepwater 3D data volumes. Instead they derived a dynamic (i.e. function of time and angle) correction that has more in common with a layer replacement technique than with vertical raypath shifts assumed for static corrections. None of these approaches accounts for vertical variation in seismic velocity, nor for the possibility that significant variations can occur during acquisition of a single line.

Meanwhile, in a landmark paper outside the hydrocarbon industry, Holbrook et al. (2003) showed that conventional reflection seismic data can provide direct images of oceanic structure. Poor quality seismic reflection images of ocean structure had previously been documented (Gonella

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and Michon, 1988; Phillips and Dean, 1991) but Holbrook et al. (2003) were the first to target standard processing techniques on the water layer to produce good quality images, and to recognize that these could significantly contribute to oceanography. Holbrook et al. (2003) used seismic data from offshore northeast Canada, and compared these images with limited ocean temperature information obtained during seismic acquisition and with the results of vertical conductivity-temperature depth (CTD) profiles acquired during separate oceanographic studies. These comparisons suggested that thermohaline (temperature and salinity) variations across internal boundaries within the water column cause sufficient velocity and density contrasts to explain the energy reflected within the water column.

The first dedicated experiment to collect both seismic reflection and oceanographic data was conducted across the continental margin offshore Norway in 2003 (Nandi et al., 2004; Holbrook and Fer, 2005; Páramo and Holbrook, 2005). The Norwegian margin seismic data showed strong reflections from the water layer, and synthetic seismograms calculated from the coincident vertical temperature and salinity profiles again suggested that thermohaline variations on the scale of the seismic wavelength were a significant cause of reflectivity. Further seismic reflection images of the ocean have been reported from the Gulf of California, the Falklands Plateau, the Faroe-Shetland Basin, offshore Iberia, western tropical Atlantic (the Leeward Islands), the Gulf of Mexico, the Solomon Islands, and offshore Ireland (Figure 2; Ocean Science Meeting, 2006).

Several different names have been applied to the new use of seismic reflection data. Solid earth seismologists have coined the terms 'seismic oceanography' and 'geophysical oceanography' to describe what is to them a new research direction. From an oceanographer's point of view, seismic reflection profiling is just the latest member of the series of techniques that have been employed in what is already known as 'acoustical oceanography'. For example, high frequency (tens to hundreds of kilohertz) reduced bandwidth echo-sounders routinely used for finding fish shoals by acoustic backscatter can also be used to study internal waves and locate turbulent patches in shallow water (Wesson and Gregg, 1994). These images share some similarities with those we have collected using conventional seismic reflection measurements, although they have greater horizontal resolution and shallower penetration. Sound has been transmitted across entire ocean basins in order to infer decade-long changes in oceanic temperature from travel time tomography. Such applications of acoustical oceanography build on over half a century of defence research. Submarines hide beneath the low velocity zone associated with the boundary between the upper water layer of high temperature gradient and the underlying layer of reduced temperature gradient,

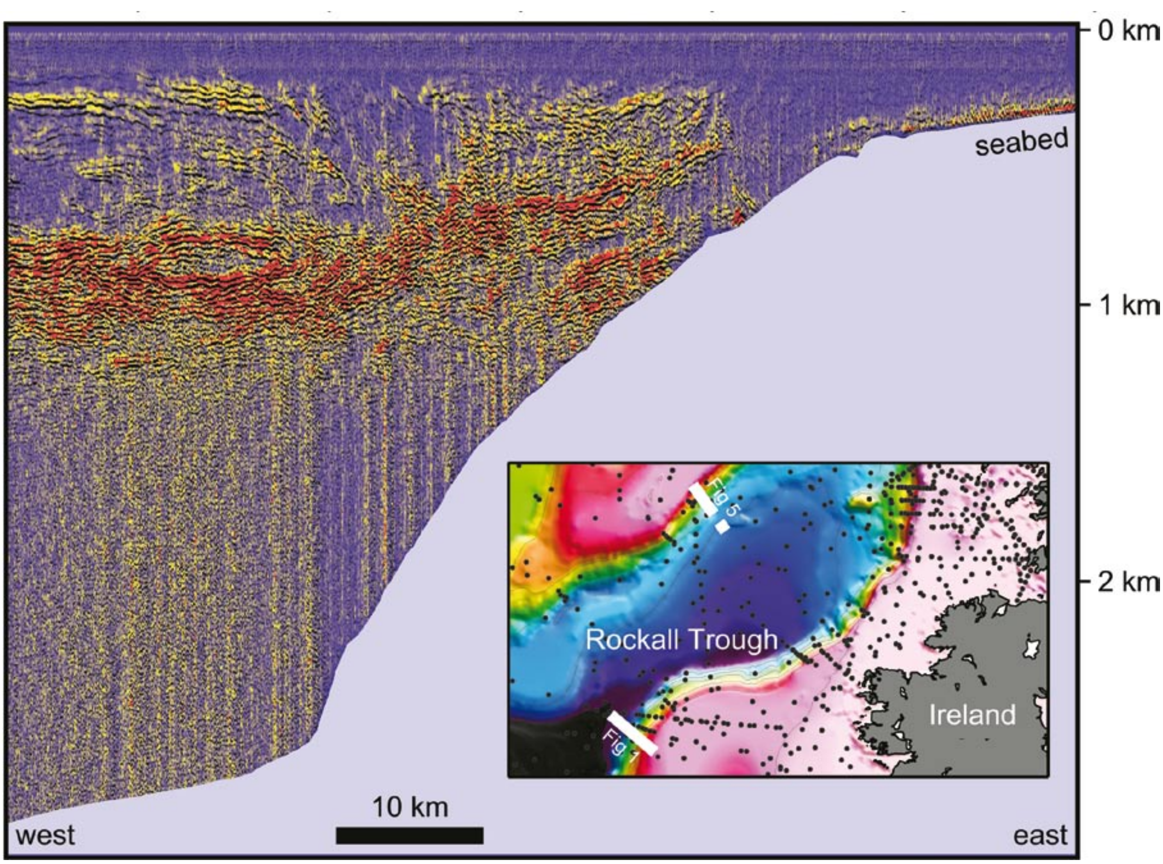

***Figure 1** Depth-converted seismic reflections from the water column within Rockall Trough, west of Ireland. A variable-area display to show the reflections (grey-scale) is superimposed on an amplitude envelope indicating reflection strength (red colour = high amplitude). Inset shows line location on SE Rockall margin with seafloor topography, and also the locations of oceanographic CTD (conductivity-temperature-depth) measurements (circles).*

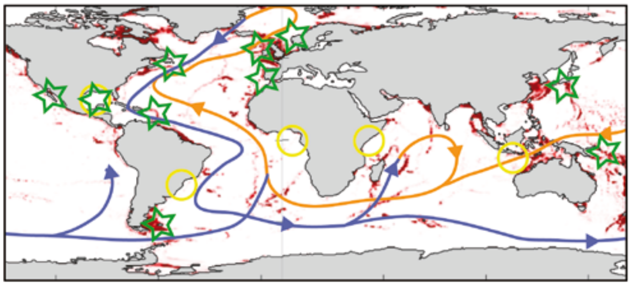

Figure 2 *Locations of combined reflection seismology/oceanography experiments (green stars) and important areas of deepwater hydrocarbon exploration (yellow circles). The global oceanic thermohaline conveyor is shown schematically by blue arrows (deep cold currents) and orange arrows (surface warm currents), and the red patches show locations where tidal energy is dissipated as tidal currents flow over steep seabed topography (Egbert and Ray, 2001); seismic water layer reflectivity may be related to both these phenomena. Many of the seismic studies have appeared in abstract form (Ocean Science Meeting, 2006) but have not yet been published in detail.*

known as the sound fixing and ranging (SOFAR) channel, exploiting the fact well known to wide-angle seismologists that a velocity inversion leads to a 'hidden layer'. Whales make use of the way sound is channelled along the same low-velocity layer to communicate across ocean basins. Technical details of these and other previous uses of sound in oceanography can be found in Medwin (2005), and a good non-specialist summary has been produced by the National Academy of Sciences (Sounding out the ocean's secrets. Link from http://www.beyonddiscovery.org/).

Processing water layer data: Rockall Trough example

We illustrate the processing sequence required to generate images of ocean structure using examples from our ongoing study of legacy reflection seismic profiles across Rockall Trough, west of Ireland. Rockall Trough is a 200 km wide sediment-starved basin defined by steep seabed slopes that descend from a depth of 200 m on the surrounding shelf to over 3 km in the basin centre (Figure 1 inset). The water is vertically stratified and several layers can be identified on the basis of temperature, salinity, and other chemical characteristics (Figure 4). A margin-parallel current sweeps anti-clockwise round the trough, medium scale (c. 100 km diameter) eddies have been documented, and internal waves are generated at both margins (internal waves propagate through the interior of the water column rather than along the sea surface). A substantial legacy seismic database is available to investigate these oceanographic phenomena, even though the region is still a hydrocarbon exploration frontier. However, before going to the time and expense of copying and loading a particular seismic survey for oceanographic study, acquisition parameters should first be screened for suitability. Some datasets were recorded with insufficient dynamic range to preserve oceanic reflections, which are about an order of magnitude weaker than subsurface reflections. Worse, a deep-sea delay may have been used to reduce the size of the dataset, so that seismic returns from the upper part of the water column were not recorded. Re-shoots and other time gaps in acquisition are not a problem, since they provide a direct means of determining short-term variability in water column reflectivity.

Both pre- and post-stack processing sequences can be applied to the seismic data, depending on the oceanographic feature to be imaged. For a solid Earth seismologist, the obvious course of action is to produce a stacked seismic reflection profile, such as the example in Figure 1, to describe the reflectivity structure, and to correlate features of interest with adjacent profiles. We aim to develop a standard processing sequence that preserves reflection amplitude and is executed rapidly, so that many different legacy surveys can be compared quickly and objectively. A simple 'normal moveout and stack' processing flow achieves these objectives and is sufficient to establish reasonable quality preliminary images for many datasets. The main components of the processing flow are: isolation of water column data; source signature removal and amplitude scaling to a common value; direct arrival removal after linear moveout and median filtering; normal moveout (NMO) correction at constant velocity (e.g., 1480 m s^{-1}); and stack. For our automated flow we prefer to use a constant velocity during NMO correction. Previous studies carried out velocity analysis; and of course this 'sharpens' the resulting images. However, since the water layer is in constant motion at speeds that could be comparable to the speed of the seismic vessel, the time versus offset geometry of the reflections is a function of water current velocity as well as acoustic velocity. Results of semblance analysis cannot therefore be directly interpreted as acoustic velocities, and even if an NMO correction based on these results is applied to obtain a sharper stacked image, the physical interpretation of undulating reflections in the stacked section is unclear. Where reflections have significant residual moveout after constant velocity NMO correction, smearing can be avoided by stacking a limited offset range only.

Although background noise levels (e.g., swell noise and cable tug) may swamp signal in some cases, in general the most problematic noise comes from direct arrivals. Figure 3a shows that the strength of the direct arrival and related ringing is much greater than the strength of the signal, although the signal

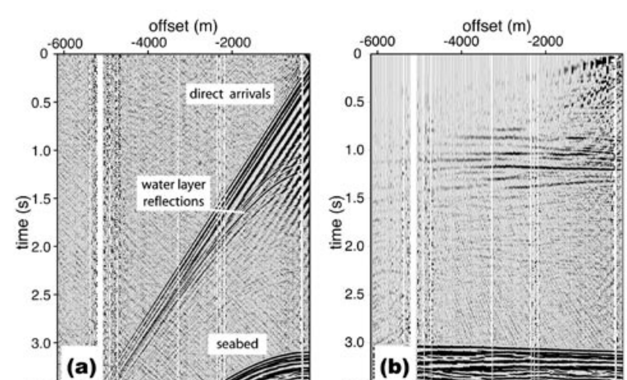

Figure 3 *Shot records to illustrate signal/noise characteristics and effect of processing. (a) Shot record of raw data (b) Same record after noise removal and NMO correction using constant velocity. Data may require further noise suppression before detailed analysis.*

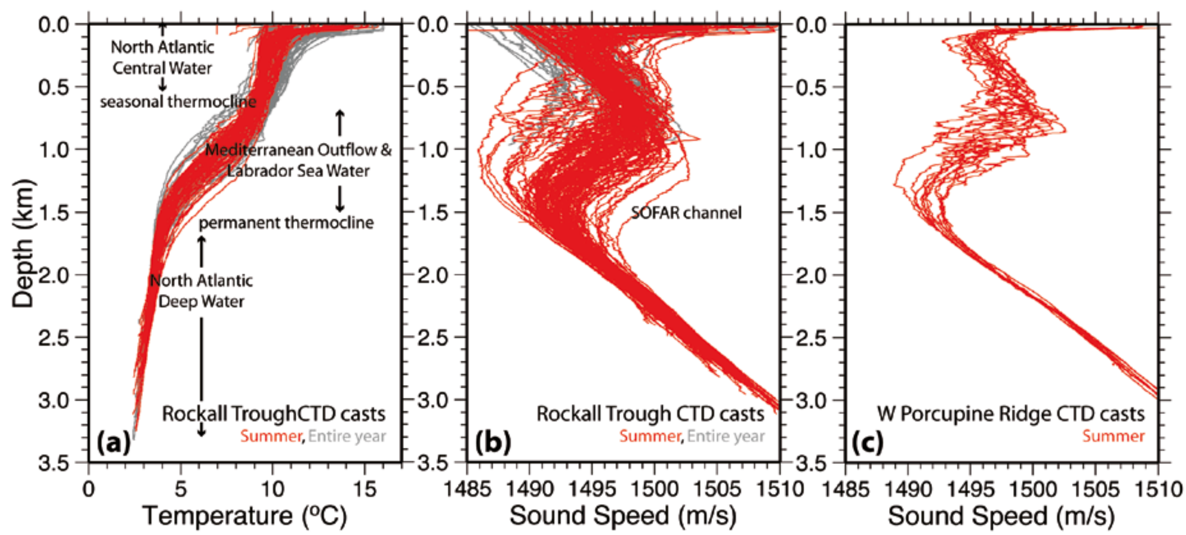

Figure 4 *Rockall Trough oceanographic data from stacked CTD records collected since the 1970s (located in Figure 1 inset). (a) Large-scale temperature profile. (b) Sound speed profiles calculated from the temperature and salinity data. (c) Subset of sound speed profiles collected during the seismic acquisition season (May to September) along the western flank of Porcupine Ridge, SE Rockall Trough (see box in Figure 1 inset). The 10–100 m scale variability above the permanent thermocline is responsible for the increased seismic reflectivity seen in Figure 1.*

itself can be clearly identified without stacking. A variety of strategies can be used to deal with direct arrival noise, depending on the depth of the target signal and whether the data are to be interpreted in pre- or post-stack form. Direct arrivals can be partially removed by the stretch mute conventionally applied to far offsets to limit the effect of moveout stretch. The advantage of this simple strategy is that the strength and frequency of the signal are completely unaltered, but a considerable amount of noise remains at shallow depths and near offsets, and at greater depths the useable offset range is less than 2 km. The processing flow outlined in the previous paragraph uses a median filter to remove some of the direct arrival noise. For many datasets, some direct arrival noise remains after median filtering and further processing is required. High-pass filtering (cut-off around 20 Hz), median filtering and Karhunen-Loève (KL) filtering have all been found successful (Ocean Science Meeting, 2006). In general, we prefer to use less severe filtering and accept some residual direct arrival noise close to the sea surface. It may not always be necessary to have good images of the shallow water, since the vigorous mixing known to characterize the surface layer could mean that any signal reflections cannot be correlated over space or time. When shallow images are required, a minimum amount of median and bandpass filtering can be used because the remaining direct arrival noise forms straight horizontal bands on a stacked section, so the eye can easily distinguish the signal by its variable dip. Harsher filtering is sometimes required for data with high levels of water column noise, and particularly for older legacy data that are spatially aliased owing to longer group intervals, but care must be taken not to lose signal at large offsets where it has time moveout similar to that of the direct arrival.

Some oceanographers have questioned the use of conventional seismic profiles in oceanographic imaging because the water layer is in constant motion, even though the same criticism can be made of oceanographic datasets collected over a limited time period. In Rockall Trough, for example, internal oceanic waves could travel at speeds up to several metres per second, while the margin-parallel current flows at 0.01–0.5 m s^{-1} (White and Bowyer, 1997). These speeds are similar to a typical seismic vessel speed of 2 m s^{-1} (4 knots). For a 6 km streamer, signal might be seen at offsets up to 4 km (Figure 3b). The ship moves 2 km to produce a common midpoint (CMP) gather with a 4 km offset, so the gather contains traces collected over 17 minutes at an acquisition speed of 2 m s^{-1}. During this time period, an internal wave crest moving at 1 m s^{-1} would move 1 km. This example suggests that conventional processing steps that mix together shot records (including CMP gathering and stacking, and common offset

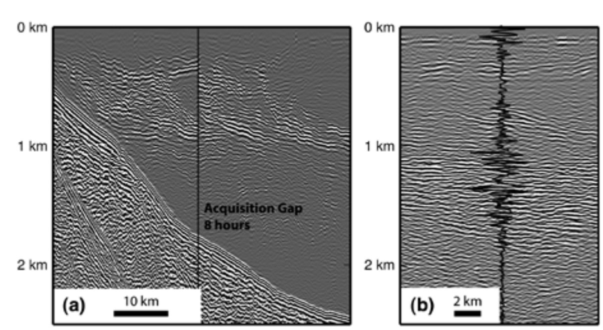

Figure 5 *Two examples from Rockall Trough to illustrate temporal variability within seismic and oceanographic datasets (located in Figure 1 inset). (a) Gap of about eight hours during acquisition of WESTLINE. Note that the overall shape of the reflective package adjacent to Rockall Bank remains the same, but a smaller package of reflections several hundred metres thick is discontinuous across the acquisition gap. (b) Example of a reasonable match between the synthetic reflection profile (based on oceanographic data) and observed seismic reflectivity, even though the seismic data and oceanographic data were collected in different years.*

or post-stack migration) could lead to significant smearing of moving targets through acquisition time (which maps into horizontal distance along a conventional profile), so that oceanographic information will be lost.

To avoid this problem, prestack processing and imaging techniques can be used to investigate potentially moving targets. Each shot record provides a snapshot image of the water column, and water motion can be assessed by comparing the same reflections on adjacent shots. For example, reflections in the shot record in Figure 3b are deformed by undulations that can be interpreted as perturbations caused by internal oceanic waves. The amplitude and frequency of the internal waves can be measured, and the propagation speed can be measured by comparison of the same reflection on successive shots. Clearly, the greater the offset range over which a reflection can be traced on each gather, the more such information on internal waves can be generated. It is therefore important not to apply a stretch mute. Receiver motion correction (Hampson and Jakubowicz, 1990) can be applied, and stretch-free moveout correction (Perroud and Tygel, 2003) can extend the available offset range.

Interpreting seismic images of the ocean

Following Holbrook et al. (2003), several studies have been carried out (Figure 2). Some experiments image mixing of major water masses, including outflow of warm salty Mediterranean waters into the Atlantic and mixing of circum-Antarctic currents with South Atlantic water. In other studies, including our examples from Rockall Trough (Figure 1), packages of high seismic reflectivity have been observed adjacent to steep seabed topography along continental slopes. Although these latter images do not appear as spectacular as the eddy, interfingering, and subduction structures observed at the major ocean mixing fronts, they may well provide significant and fundamental advances in our understanding of global oceanic mixing processes.

What causes the seismic reflectivity? All published studies have argued that temperature and salinity variations on the scale of the seismic source wavelength (1–20 m) are important. Thermohaline structure on this scale is termed 'fine-structure' by oceanographers. Nandi et al. (2004) acquired coincident datasets offshore Norway by deploying expendable oceanographic probes from the seismic vessel during shooting. Synthetic seismograms calculated from the temperature and salinity data provided a good match to the seismic data and suggested that seismic reflectivity was influenced by temperature variations of as little as 0.05°C over a 10–20 m interval. Páramo and Holbrook (2005) used amplitude versus offset analysis to demonstrate that temperature has the dominant effect on seismic velocity offshore Norway. In other areas of the world, particularly in shallow water, salinity can have the greater effect. Water layer reflection coefficients around 0.0014 have been estimated by Tsuji et al. (2005) offshore Japan, using the method of Warner (1987) to compare the strengths of water layer and water bottom reflections.

Experience in other branches of acoustical oceanography suggests that other effects, such as scattering and refraction, might contribute to the energy returned from the water layer (Medwin, 2005). No published studies have explored these ideas in relation to seismic reflection data. However, several features of our Rockall dataset suggest that thermohaline fine-structure alone cannot explain all observed reflectivity. For example, reflections that dip more steeply than the density contours calculated from oceanographic measurements are sometimes observed. Furthermore, we often observe that the reflective package associated with the SOFAR channel becomes thicker (its top becomes shallower) and more strongly reflective close to the steep seabed slopes at the trough margin. However, a compilation of legacy oceanographic data shows no obvious difference in average thermohaline fine structure between the basin centre and margins. We therefore believe that the question of what exactly is causing the water layer reflectivity is not yet properly understood. However, more seismic observations such as those in Figures 1 and 5 should help in answering this question. We are in the process of mapping seismic water layer reflectivity around all the margins of Rockall Trough.

Before seismic maps of oceanic structure can be used to full effect, we need to know the temporal and spatial variability of the reflectivity. Addressing this issue is currently an active area in the synergy between oceanography and seismic reflection imaging. Two end-member strategies are being pursued. One is to perform benchmark calibration studies that involve collection of simultaneous and co-located seismic and oceanographic data. For example, one of us (Hobbs) is leading the EU-funded Geophysical Oceanography (GO) project (www.dur.ac.uk/eu.go). This collaboration has collected a large combined dataset from the Gulf of Cadiz, where mixing of Mediterranean outflow water and mixing adjacent to continental slope topography are known to occur. The project will also generate a synthetic seismic dataset from theoretical models of the ocean. These two datasets will then be analyzed to assess what oceanographic parameters can be reliably extracted from the seismic data, and also to design optimum acquisition, processing and interpretation strategies for future seismic experiments.

A second strategy for answering the time/space variation question is to make use of the very large pool of legacy seismic data. Considering the typical current speeds mentioned in the previous section, we should not necessarily expect to be able to correlate individual reflections imaged more than an hour apart. The sharp discontinuity in reflectivity structure seen after an eight-hour break in shooting of WESTLINE confirms this prediction (Figure 5a).

In future, it is possible that seismic water layer images will be interpreted using concepts borrowed from the study of turbulence. In this strategy, it is important to measure the degree of correlation of some seismic property as a function of the space and time. Using data from a dedicated seismic/oceanographic experiment offshore Japan, Tsuji et al. (2005) showed that individual reflections can be traced over distances up to 40 km and correlated on images acquired several days apart. Legacy datasets can be mined for similar measurements by comparing lines and cross-lines within a single survey and co-located lines from different surveys. We have begun to make temporal and spatial variability measurements using 2D seismic grids in SE Rockall Trough, and several other groups have published abstracts on analysis of legacy datasets (Ocean Science Meeting, 2006), but no detailed results have yet been published. Hydrocarbon industry experience summarized at the start of this paper clearly shows that a large amount of information on temporal variation within the water layer is contained in 3D seismic surveys. Travel time variations at swath boundaries constrain variability over time periods of several hours to several weeks, while 4D surveys provide additional comparisons over several years. No work on the use of 3D or 4D seismic data in oceanography has yet been published.

In addition to the strategies of acquiring joint seismic/oceanographic academic datasets and analyzing legacy industry datasets, we propose a third approach that represents a middle way. The oil industry is encouraged to acquire oceanographic data using expendable probes deployed from a chase boat during the acquisition of 3D surveys, and to make the oceanographic measurements and the water column part of seismic data available for academic research.

Benefits to oceanography

The oceans and atmosphere play a fundamental role in controlling climate. Oceanography is essentially a field subject, and progress in understanding ocean circulation depends on improved observations of basic quantities such as temperature, salinity, and current velocity. The deep ocean is vast and ever-changing, so direct sampling techniques make inefficient mapping tools. Traditionally, oceanographers build models of thermohaline structure using vertical CTD profiles, acquired by lowering a probe from a stationary boat. It can take many hours to measure a single vertical profile in deepwater. Various strategies are available to improve data coverage, such as fixing CTD probes to yo-yo systems that move up and down within the water column behind a moving boat, or deploying expendable probes that transmit data back to a moving ship. Nevertheless, in order to realize a step-change in mapping 3D oceanic structure it is necessary to combine direct measurements with remote sensing techniques that can survey large areas rapidly.

Satellite observations are now routinely used to monitor sea surface temperature across the entire globe, and this blanket data coverage has resulted in a significant improvement in coupled ocean-atmosphere computer models. Our hope is that legacy and newly acquired seismic reflection data will lead to a similar step-change in mapping 3D oceanic structure down to the seabed, particularly around continental margins where most industrial seismic data are acquired. Seismic reflectivity maps might be used to decide on the locations of seabed oceanographic observatories that communicate continuous multiple data streams back to land in real time, which are increasingly important tools in modern deepwater oceanographic exploration. When the scales of spatio-temporal variation have been measured, the maps might also be used to extrapolate outward from oceanographic point measurements, much as seismic datasets are used to extrapolate outward from well data in the hydrocarbon industry. In future, when the cause of the seismic reflectivity is better understood, the seismic maps themselves might be used to investigate oceanic mixing processes. Mixing is important because it maintains global thermohaline circulation (Munk and Wunsch, 1998). Ability to image variation in vertical mixing at continental margins around the world would significantly enhance the predictive capabilities of computer models of ocean circulation and climate change.

Benefits to hydrocarbon industry

Ability to predict the spatial and temporal scales of thermohaline fine-structure will also benefit both exploration and field management. For example, an initial 2D or 3D seismic survey could be analyzed to establish the characteristic spatial and temporal variations in water layer velocity. This information could be used to optimize the acquisition of repeat 3D surveys required for monitoring field development, in order to minimize static shift and amplitude variation problems. It is important to know the strength and variability of ocean currents when planning drilling operations or seabed installations. When designing production facilities, it is important to know the range and timescale of ocean temperature variation, which strongly affects the viscosity of oil as it is pumped from seabed to sea-surface. Seismically derived maps of oceanic structure provide an intelligent way of estimating likely current and temperature variations in a large volume surrounding sparsely located direct measurements. More generally, oceanic currents also control the shape and stability of the continental slope.

The political and environmental capital that could be made from using industry data for green purposes is at least as important as the direct technological benefits. The hydrocarbon industry is regularly criticized for facilitating greenhouse warming by supplying carbon dioxide and methane to the atmosphere. Now the industry has the opportunity to take a prominent role in researching the climate system. We also hope that the industry will begin to adopt two new policies when acquiring new seismic reflection data. The first is to routinely supply a copy of the water layer part of all new data for academic research. Confidentiality would not be a problem because the sub-seabed data could be automatically stripped from the academic copy using standard processing procedures. The second policy is to routinely deploy inexpensive expendable oceanographic probes during seismic surveys. Adoption of these policies could significantly benefit society at minimal cost to the industry. We have established a consortium of interested universities, oil companies, and seismic acquisition contractors. The MOST (mapping oceans using seismic traverses) project will process legacy seismic data using standard routines and provide the images for academic research in oceanography and climate.

Conclusions

Our principal aim has been to show the hydrocarbon industry that its seismic data is of potentially great importance in oceanography. Existing processing tools can be used to generate seismic images of oceanic structure, but care must be taken when using processing steps that average data over acquisition time. Important questions that will be tackled over the next few years are what causes the seismic reflectivity, and how does the seismic reflectivity vary through space and time? We have presented the first images of oceanic thermohaline structure in the Rockall Trough, offshore Ireland, to illustrate these processing and interpretation questions. At present, an important benefit for oceanography is that internal wave characteristics can be measured using stacked sections and single shot gathers.

In future, when the link between seismic reflectivity and oceanographic processes is better understood, it might be possible to interpret 3D seismic maps in terms of variations in mixing, which would significantly enhance the predictive capabilities of computer models of ocean circulation and climate change. Implications for the oil industry are that a greater understanding of oceanographic processes can aid deepwater exploration, particularly in situations involving 4D seismic or multiple suppression, drilling and development, particularly involving seabed installations. We propose that the hydrocarbon industry should routinely donate ocean layer seismic data to a data bank with free access for researchers studying ocean and climate processes, and routinely deploy disposable oceanographic probes from the guard boat to enhance the value of the new data for ocean and climate studies. We have established the MOST consortium (www.most-project.org) to facilitate such data exchange.

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References

Barley, B. [1999] Deep-water problems around the world. *The Leading Edge,* **18**, 488–494.

Bertrand, A. and MacBeth, C. [2003] Seawater velocity variations and real time reservoir monitoring. *The Leading Edge,* **22**, 351–355.

Egbert, G.D. and Ray, R.D. [2001] Estimates of M2 tidal energy dissipation from TOPEX/ Poseidon altimeter data. *Journal of Geophysical Research,* **106**, 22475–22502.

Gonella, J. and Michon, D. [1988] Ondes internes profondes revelées par sismique reflexion au sein des masses d'eau en Atlantique-Est. *C. R. Acad. Sci. Paris,* **306**, 781–787.

Hampson, G. and Jakubowicz, H. [1990] Effects of source and receiver motion on seismic data. *60th SEG Annual Meeting*, Expanded Abstracts, 859–862.

Holbrook, W.S. and Fer, I. [2005] Ocean internal wave spectra inferred from seismic reflection transects. *Geophysical Research Letters,* **32**, L15604.

Holbrook, W.S., Páramo, P., Pearse, S. and Schmitt, R.W. [2003] Thermohaline fine structure in an oceanographic front from seismic reflection profiling. *Science*, **301**, 821–824.

Lacombe, C., Schultzen, J., Butt, S. and Lecerf, S. [2006]. Correction for water velocity variations and tidal statics. *68th EAGE Conference & Exhibition*, Extended Abstracts, P098

Mackay, S., Fried, J. and Carvill, C. [2003] The impact of water-velocity variations on deepwater seismic data. *The Leading Edge,* **22**, 344–350.

Medwin, H. [2005] *Sounds in the Sea: from Ocean Acoustics to Acoustical Oceanography.* Cambridge University Press.

Munk, W. and Wunsch, C. [1998] Abyssal recipes II: Energetics of tidal and wind mixing. *Deep Sea Research I*, **45**, 1977–2010.

Nandi, P., Holbrook, W.S., Pearse, S., Páramo, P. and Schmitt, R.W. [2004] Seismic reflection imaging of water mass boundary in the Norwegian Sea. *Geophysical Research Letters*, **31**, L23311.

Ocean Science Meeting [2006] *EOS, Tranactions of the AGU*, **87**(36), Ocean Science Meeting Supplement, Sessions OS13I, OS14I & OS16G.

Páramo, P. and Holbrook, W.S. [2005] Temperature contrasts in the water column inferred from amplitude-versus-offset analysis of acoustic reflections. *Geophysical Research Letters*, **32**, L24611, doi:10.1029/2005GL024533.

Perroud, H. and Tygel, M. [2004] Nonstretch NMO. *Geophysics*, **69**, 599–607.

Phillips, J.D. and Dean, D.F. [1991] Multichannel acoustic reflection profiling of ocean watermass temperature/salinity interfaces. In: Potter, J. and Warn-Varnas, A. (Eds.) *Ocean Variability and Acoustic Propagation*. Kluwer Academic Publishers, Dordrecht, 199–214.

Tsuji, T., Noguchi, T., Niino, H., Matsuoka, T., Nakamura, Y., Tokuyama, H., Kuramoto, S. and Bangs, N. [2005] Two-dimensional mapping of fine structures in the Kuroshio Current using seismic reflection data. *Geophysical Research Letters*, **32**, L14609, doi:10.1029/2005GL023095.

Warner, M. [1990] Absolute reflection coefficients from deep seismic reflections, *Tectonophysics*, **173**, 15-23.

Wesson, J.C. and Gregg, M.C. [1994] Mixing at Camarinal Sill in the Strait of Gibraltar. *Journal of Geophysical Research*, **99**, 9847–9878.

White, M. and Bowyer, P. [1997] The shelf-edge current north-west of Ireland. *Annales Geophysicae*, **15**, 1076–1083.

Wombell, R. [1997] Water velocity variations and static corrections in 3D data processing. *59th EAGE Conference and Exhibition*, Extended Abstracts, A029.

Xu S. and Pham, D. [2003] Global solution to water column statics: a new approach to an old problem. *73rd SEG Annual Meeting*, Expanded Abstracts, 1885-1888.

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