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Seismic Oceanography: A New Geophysical Tool to Investigate the Thermohaline Structure of the Oceans

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1. Introduction

Seismic oceanography is a new cross discipline between seismology and physical oceanography. It consists of the application of the multichannel seismic reflection method, commonly used in the oil industry to image the subsurface geological structure, to the investigation of the thermohaline fine structure of the oceans. The application of the seismic reflection method for this purpose was first reported by Gonella and Michon (1988), but that work remained largely unknown, and it was not until its rediscovery and the publication of the work of Holbrook et al. (2003) that this new method became widely established.

Seismic reflection sections provide very high resolution images of the oceans structure, both vertical and, in particular, horizontal, and complement conventional physical oceanography CTD/XBT data (e.g. Ruddick et al., 2009). These images consist of seismic reflections that occur and are recorded whenever a seismic wave travelling in a heterogeneous media encounters interfaces between different water masses with different acoustic impedances (the product of density by sound speed) and is reflected back to the surface. Nandi et al. (2004) and Nakamura et al. (2006) have shown that the reflectors imaged correspond indeed to oceanic thermal structures and, more recently, Ruddick et al. (2009) have shown that temperature variations have the dominant contribution to acoustic impedance contrasts and that salinity variations strengthen impedance contrasts by O(10%). Since the salinity variations are highly correlated with temperature variations on the scales that reflect sound, they enhance but do not change the appearance of reflectors. Therefore, these authors further demonstrated that seismic images of the water column are primarily images of vertical temperature gradient smoothed over the resolution scale of the seismic source wavelet, typically ~10m. Ocean "fine-structures" of that order of dimension are well-known in the ocean and are associated with a variety of physical phenomena: internal waves, thermohaline intrusions, double-diffusive layering, mixed water patches, vortical modes, and others (Ruddick et al., 2009).

Compared to conventional methods for investigating the ocean used in physical oceanography, seismic oceanography has the advantages of high lateral resolution and fast imaging (typical horizontal sample rate is about ten meters but time sample rate is far less, although with lower vertical resolution than conventional physical oceanographic methods). Holbrook and Fer (2005) have made quantitative inferences about internal wave energy levels near sloping ocean bottom that may eventually link to internal wave reflection properties and near-bottom ocean mixing. As noted by Ruddick et al. (2009), similar to satellite images that clearly show mixing events around the edges of structures like the Gulf Stream, Warm Core Rings, and eddies, seismic images allow us to synoptically see the relationships between finescale structures and the mesoscale features (like eddies) that produced them. Images that show the links from mesoscale features to finescale features that are associated with mixing allows hypotheses about the causes and consequences of mixing to be developed and tested in ways not previously possible. As noted also by Ruddick et al. (2009), being images of temperature gradient, seismic images are closely analogous to Schlieren images, which revolutionized laboratory fluid dynamics by showing how small-scale details relate to larger structures. This is the most exciting promise of seismic oceanography: synoptic visualization of features such as eddies and their associated fine structures allows the relationship between them to be explored in a new way. Since mixing generally passes energy from mesoscale features to fine scales, then to turbulence and molecular dissipation, this visualization tool provides a new insight into important stages in the energy cascade (Ruddick et al., 2009).

The method has thus far been successfully applied to image water mass fronts, currents, boundaries, mesoscale features such as cyclones, intrathermocline eddies, Meddies and the Mediterranean Undercurrent, staircases and internal waves (e.g. Holbrook et al., 2003; Holbrook et al., 2005; Tsuji et al., 2005; Schmitt et al., 2005; Nakamura et al., 2006; Biescas et al., 2008; Krahnemann et al., 2008; Song et al., 2009, 2010; Dong et al., 2009; Hobbs et al., 2009; Klaeschen et al., 2009; Sheen et al., 2009; Pinheiro et al., 2010).

In the development of seismic oceanography, inversion of the seismic data to obtain quantitative physical properties, such as sea water sound speed, temperature and salinity is now one of the key problems. In order to build benchmark calibration between reflection seismic and oceanographic datasets and make further progresses in seismic oceanography, EU launched the interdisciplinary GO (Geophysical Oceanography) project in 2006 for seismic and oceanographic joint investigation (http://www.dur.ac.uk/eu.go/general_public/project_info.html). This has allowed for the first time to get a dedicated dataset with near simultaneous acquisition of seismic and oceanographic data which provided essential for the first inversion tests (Papenberg et al. 2010; Huang et al., 2011). This work introduces the basic principles of the seismic method, shows results of its application to obtain high spatial resolution images of ocean eddies, lateral intrusions and internal waves, and presents preliminary results of CTD/XBT-controlled wave impedance inversion to derive the detailed thermohaline structure. In this paper, we briefly review the principles and limitations of the multichannel seismic technique as applied to the water column (section 2), show several examples of physical oceanographic phenomena that can be imaged with the technique (section 3), and discuss inversion techniques used to obtain highly detailed temperature and salinity sections from combined seismic and hydrographic data (section 4).

2. The multichannel seismic reflection method

Multichannel reflection seismology has been used for decades as an efficient exploration method, both in fundamental research and in the oil industry, because it allows a detailed

acoustic imaging of the subsurface geology, both onshore and offshore (see, for example, Sheriff and Geldart, 1995). Offshore, the seismic (or acoustic) signal is normally generated by an array of airguns, towed behind a ship, a few meters below the water surface. These airguns release sudden bubble-pulses of compressed air into the water, as the ship navigates (Figure 1). This acoustic energy propagates downward in the water layer, and a fraction of it is reflected back to the surface whenever it encounters a contrast in the acoustic impedance between water masses with different temperature, salinity and/or density. The upward propagating reflected acoustic energy is detected at the surface by an array of piezoelectric sensors (hydrophones), commonly known as a *streamer of hydrophones* and is recorded digitally; these hydrophones are organized into groups (active sections) in which the signals are summed together to get a better signal-to-noise-ratio; each group forms a channel and common 2D systems can have between 96 and more than 500 channels (Figure 1). The processed signal conveys the necessary information to derive structural and physical information of the layers through which the acoustic energy propagated.

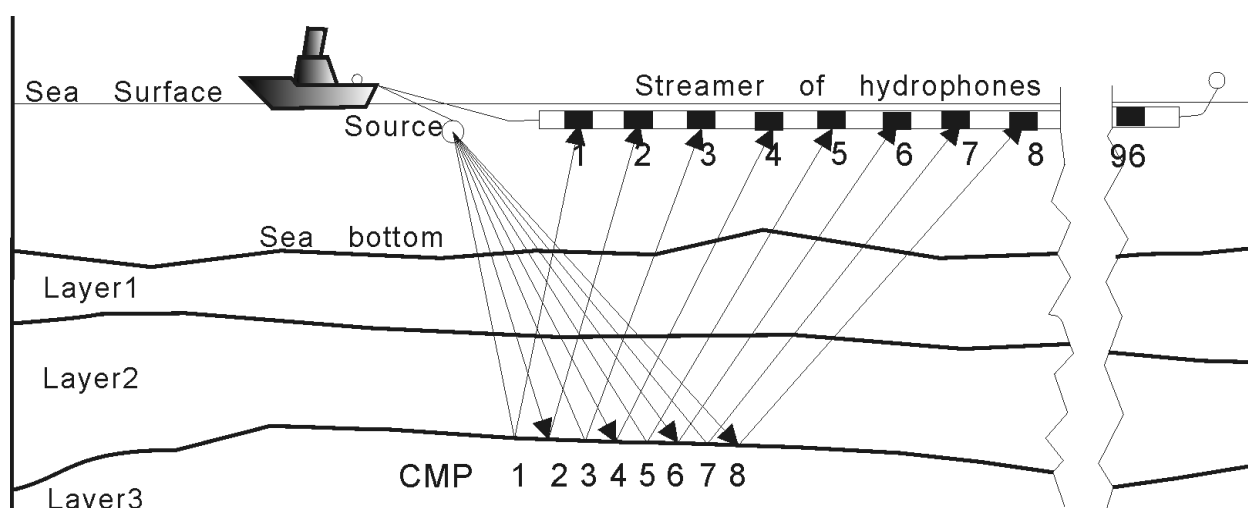


Fig. 1. Schematic illustration of the marine multichannel reflection seismic acquisition method.

In order to enhance the signal-to-noise ratio, obtain a near vertical reflection signal and derive the sound speed in the different propagation medium layers, the so-called *Common Mid Point Method* (CMP) is generally used. The returned reflected signal from each shot is recorded in all the active channels and this constitutes a *Shot Gather* composed of the seismic traces recorded at each channel. After editing bad seismic traces, correcting for wave amplitude decay with distance (spherical divergence correction) and filtering undesirable noise, all the traces from different shots that correspond to reflections from a *Common Mid Point* (CMP-points with a common half distance, or *offset*, between the source and the receiver) are ordered into *CMP Gathers*, in function of increasing *offset*. Then, all the reflections in each trace that correspond to common reflection points are corrected for varying offset distance and travel time (*Normal Moveout Correction - NMO*) and summed (stacked) together, to obtain a *Stacked Section* with a much higher signal-to-noise ratio than any single channel section. This stacked section represents the response that would be generated by waves that travel vertically downward and are reflected to a virtually coincident source and receiver location. If the seismic sections include reflection events with a significant dip, this effect should be corrected, as the simplistic approach explained above is only correct for horizontal layering. This can be done through a processing step called *Migration* of the seismic section, which can be performed before or post-

stack (for a detailed discussion on these topics, the reader is referred to Sheriff and Geldart, 1995 and Yilmaz, 2001). When reflector dips are not too significant, as in seismic oceanographic data, the effect of migration is small and, as pointed out by Holbrook et al. (2003), the artifacts often produced by migration algorithms sometimes degrade the seismic image; therefore, seismic oceanographic data is sometimes presented unmigrated.

Normally, the seismic sections are plotted with the vertical axis in “two-way travel time (TWT)”, because this is the measured parameter (similar to the fact that physical oceanographers normally plot their data against in pressure, rather than in depth). Conversion from TWT to depth can be done using the velocity/depth functions derived from the hyperbolic velocity analysis carried out during the application of the *Normal Moveout Correction*. As a simplistic first approach these sections can be converted from time to depth assuming a constant sound speed of 1500 ms^{-1} so that $1000 \text{ ms TWT}=750\text{m}$ water depth. The individual seismic traces in a section are plotted side by side, usually using a two-color palette to show positive and negative reflection peaks producing the seismic image of the underlying structure. A simplified description of the methodology, assumptions and approximations of reflection seismology in the ocean, including limitations on vertical resolution set by the sound source, the effect of source wavelet side lobes, Fresnel Zone limitations on horizontal resolution, and the application of migration techniques to compensate dip, are described in Ruddick et al. (2009); for a more generalized discussion on the seismic reflection method, the reader is again referred to Sheriff and Geldart (1995) and Yilmaz (2001).

3. Some examples of thermohaline fine structure imaged with the reflection seismic method

3.1 Imaging of Mediterranean Outflow Eddies (Meddies)

Multichannel seismic sections have proved an excellent tool to investigate eddies in the oceans (Biescas et al., 2008; Pinheiro et al., 2010). Figure 2 shows the location of an approximately E-W and 326-km long multichannel seismic line acquired in the Tagus Abyssal Plain off west and south Iberia (Figure 2), in 1993, in the scope of the Iberian Atlantic Margins (IAM) Project, under the JOULE Programme, funded by the European Commission (Banda et al., 1995). This seismic line was acquired with a 4.8 km long analogue streamer, with 192 channels and a group interval of 25 meters, towed at an average depth of 15 m. The shot interval was 75 m and the sampling interval was 4 ms. The near offset was 254 m. The seismic source consisted of a 36 airgun array with a total volume of 7524 ci. Figure 3 shows an example to the type of detailed imaging of the thermohaline structure of several mesoscale features within the water column that can be obtained with the seismic reflection method (see location of the seismic line in Figure 2). This image was obtained in 2004 (Song and Pinheiro, unpublished data, 2004) and a refined processed and interpreted version was published by Pinheiro et al. (2010).

The spacing between CMP's is about 12.5m, which provides a very high horizontal resolution, allowing subtle lateral variations within the eddy and lateral intrusions to be observed; which could not be observed with conventional physical oceanographic data. Besides a large meddy observed in the eastern most portion of the section (Figures 3 and 4) and a cyclone observed in the western portion, the central portion of this line shows a complex structure within a meddy whose origin is discussed in Pinheiro et al. (2010). Images with such a high lateral resolution provide new insights into the fine structure in the oceans and will hopefully contribute to a deeper understanding of the detail of mixing processes in the ocean.

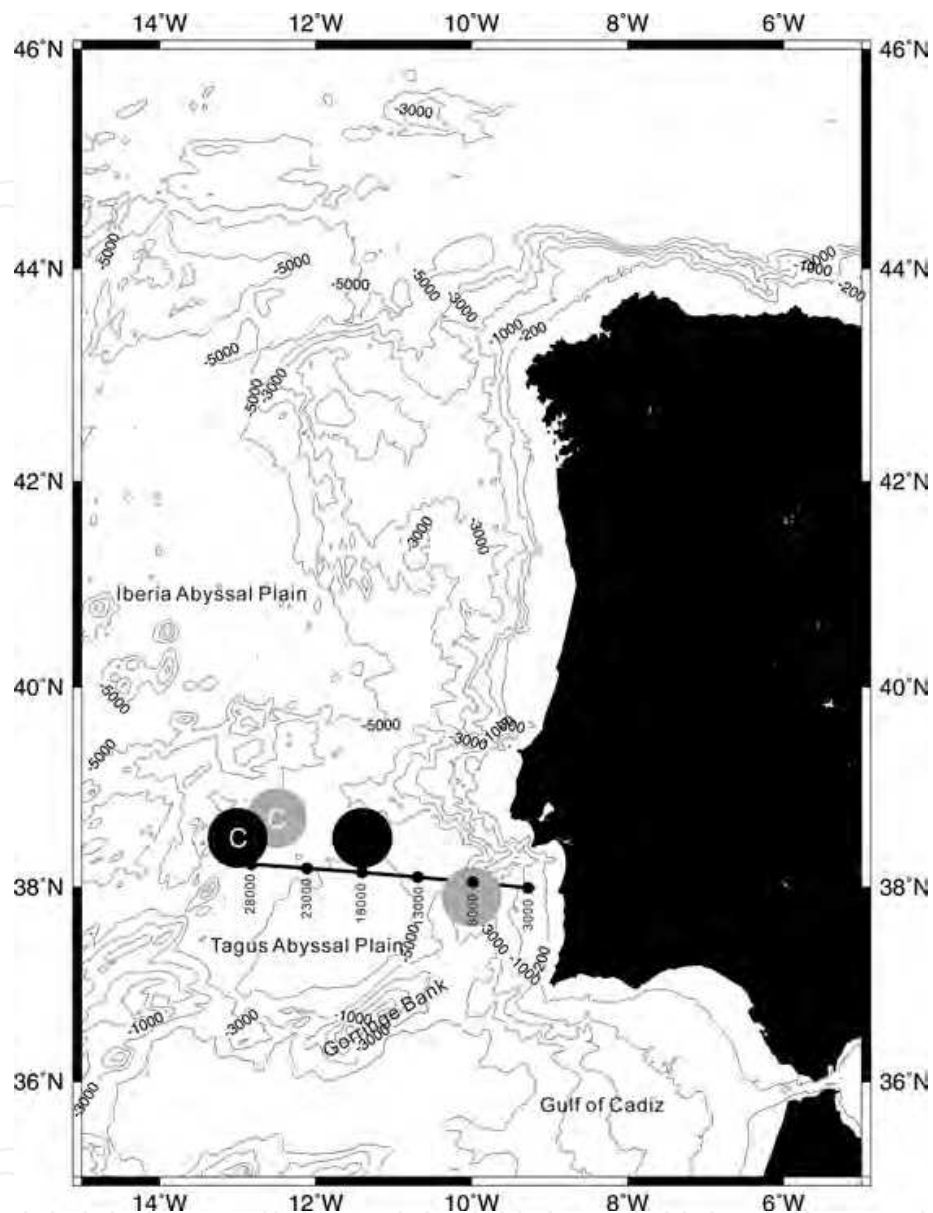


Fig. 2. Bathymetric map of the west Iberian margin showing the location of the multichannel seismic Line IAM-5 from the IAM cruise. Bathymetry from the GEBCO 1' compilation grid. Also shown the location of Meddy-9 and the cyclone C from Richardson et al. (2000) that were used to confirm the seismic interpretation; the positions of these features for August 1993 are represented as grey circles and those corresponding to September are represented as black circles. The two westernmost circles correspond to the cyclone and the two easternmost circles to Meddy-9. Also shown the location of the CMPs along the line, for reference.

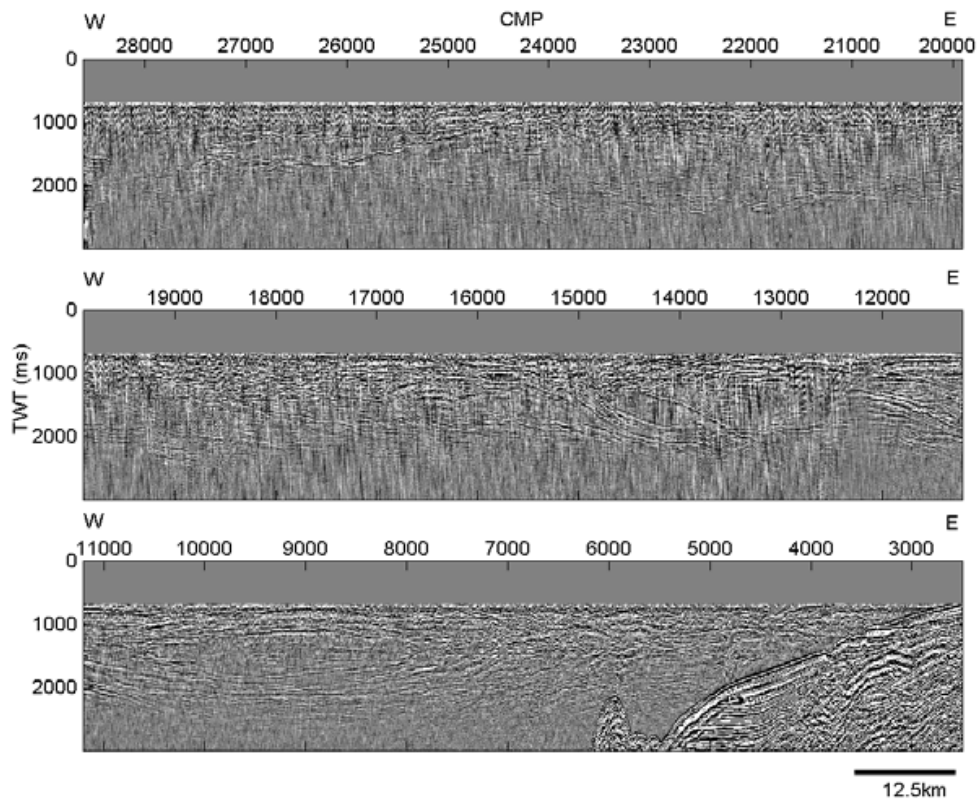


Fig. 3. Complete stacked seismic section along the processed Line IAM-5 (2004 processed version of Pinheiro et al., 2010). The vertical scale is in Two-Way Time (seconds) and the numbers in the horizontal scale correspond to CMP locations.

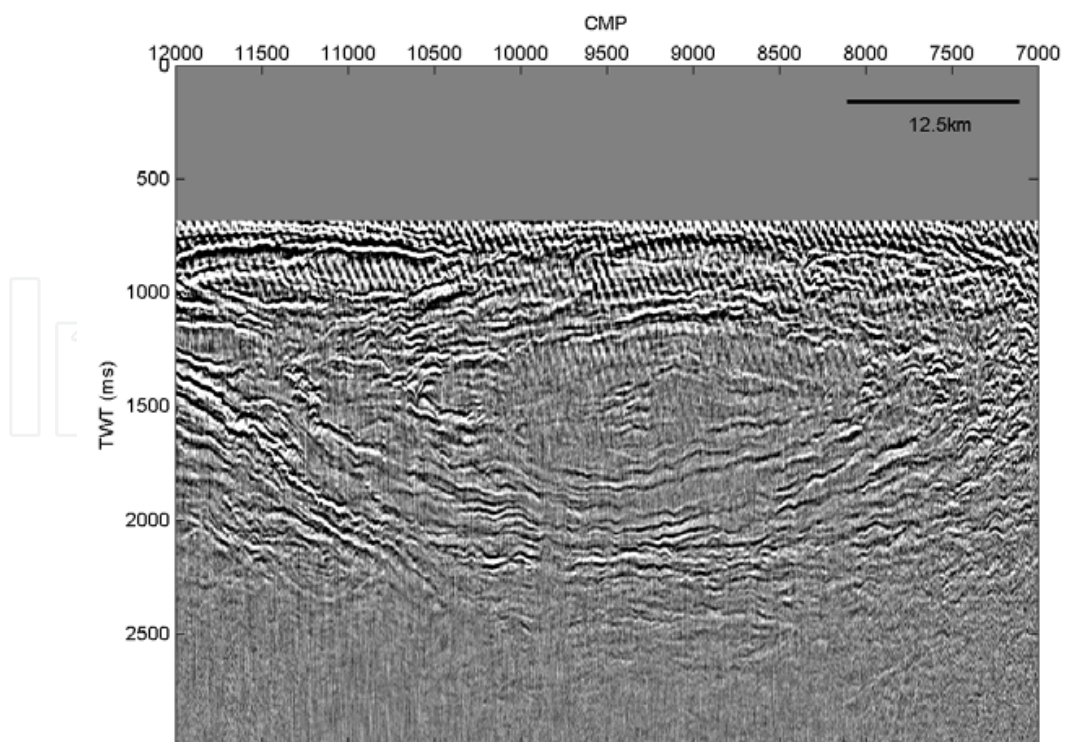


Fig. 4. Detail of Figure 3, showing a high resolution seismic image of a meddy (Song and Pinheiro, unpublished data, 2004). Several smaller lenses are also observed above the main eddy.

3.2 Imaging of internal waves in the South China Sea

Another successful application of the seismic reflection method is to image internal wave patterns with great detail, as first shown by Gonella and Michon (1988) and later by Holbrook and Fer (2005) and Blacic and Holbrook (2009). Figure 5 shows the location of a 463 km long multichannel seismic profile acquired in the Luzon Strait area, in the Northeast South China Sea (SCS); some portions of this line, highlighted in red, in Figure 5, are depicted in Figure 6. This multichannel seismic line was acquired in the framework of the National Major Fundamental Research and Development Project of China (No. G20000467), in 2001, using the R/V Tanbao of the Guangzhou Marine Geological Survey. The seismic signals were recorded by a 240-channel streamer, with a 12.5m group interval, and were sampled at 2ms. The total record length is 10s (Two-Way Travel Time - TWT) and the source to near trace offset is 250 m. The seismic source used was a 3000 in³ air-gun array. These sections show in great detail undulating seismic reflectors, coherent over vertical and horizontal distances of order 1 km, that correspond to internal waves. They provide detailed images of the lateral and vertical continuity of internal waves, allow the calculation of horizontal, as well as vertical spectra of internal waves (Song et al., in prep.) and therefore contribute to a better understanding of these phenomena.

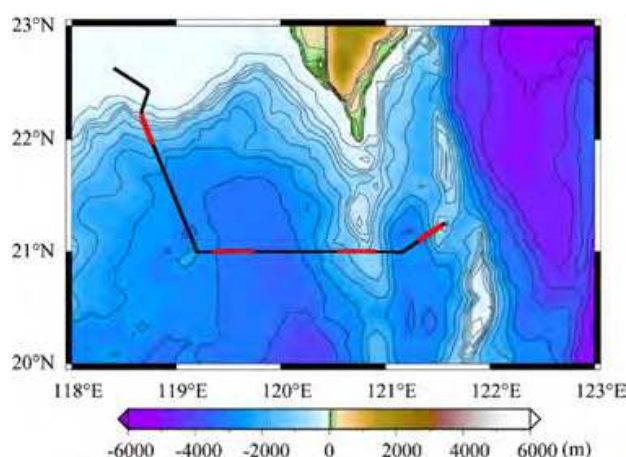


Fig. 5. Location of one seismic line acquired in the Luzon Strait, in northeastern South China Sea, whose seismic sections highlighted in red are depicted in Figure 6.

4. Thermohaline structure inversion of seismic data

Inversion for oceanographic parameters of temperature and salinity from seismic data is a very important research field in seismic oceanography. In its early stage, seismic oceanography paid more attention to imaging boundaries between water masses in the ocean (e.g. Holbrook et al., 2003; Nandi et al., 2005; Nakamura et al., 2006) and discriminating and interpreting reflection events in the seismic sections, rather than inverting acoustic impedance for physical oceanographic parameters. This was mainly due to the fact that there were not many situations in which both seismic and oceanographic data had been acquired simultaneously. As stated above, after analyzing XBT (Expendable Bathythermograph) and XCTD (Expendable Conductivity-Temperature-Depth) derived oceanographic data combined with seismic data, Nandi et al. (2005) found that reflections in the seismograms and thermohaline fine structures in the ocean were strongly correlated with each other, demonstrated that reflectors can originate from temperature changes as

small as 0.03 degree, and anticipated that high-resolution spatial distribution of temperature could be derived from the seismic sections. Tsuji et al. (2005) also confirmed that seismic sections could image fine structure of the Kuroshio Current and, through analysis of the amplitude of the seismic signal, found the maximum change of temperature observed in that area was about 1 degree. These results therefore inferred that temperature could be inverted from seismograms. Subsequently, Paramo et al. (2005) retrieved temperature gradients in the Norwegian Sea using the AVO (Amplitude Versus Offset) method, and Wood et al. (2008) applied full wave inversion to synthetic seismograms and real seismic data, with good results; however, both of these studies were restricted to 1-D. More recently, Papenberg et al. (2010) presented high-resolution 2-dimensional temperature and salinity distributions derived from inversion applied to combined seismic and physical oceanographic experiment conducted in the scope of the GO (Geophysical Oceanography) European project, and showed that seismic data can indeed provide reliable estimates of high resolution temperature and salinity, provided it is constrained by physical oceanographic data.

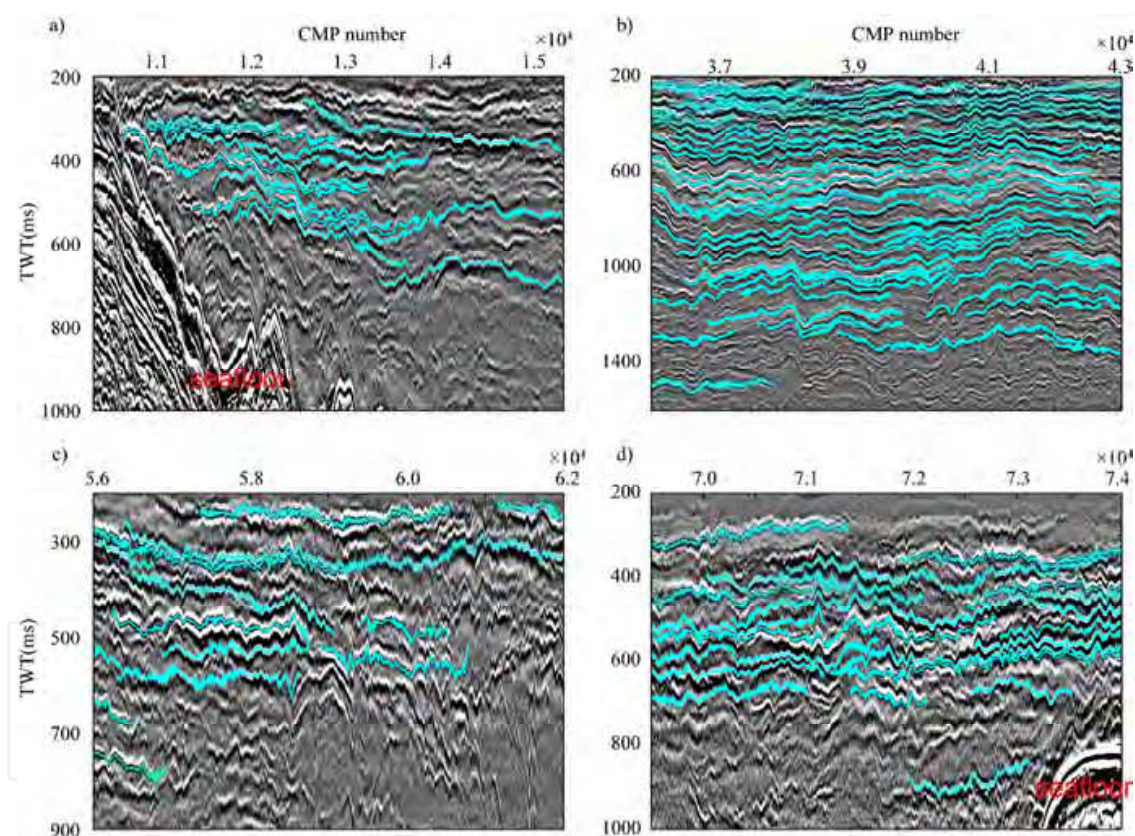


Fig. 6. Seismic sections along the seismic profile in the northeastern SCS shown in red, in Figure 5, and digitized undulate seismic reflectors (blue curves). a), b), c) and d) show sections across the continental slope, abyssal basin, Hengchun ridge and Luzon volcanic arc respectively. Vertical scale in Two Way Traveling Time (ms), CMP interval is 6.25m.

Here, we present a CTD/XBT constrained thermohaline structure inversion method (Huang et al., 2011). Using this method and synthetic seismograms Song et al. (2010) first demonstrated that it was possible to derive 2D high-resolution temperature and salinity sections from seismic data by using only a few CTD data to constrain the inversion (the

CTDs acted here as control wells in conventional seismic inversion for geological structure). This method was applied to low frequency seismic data from one multichannel seismic (MCS) line (line GOLR-12), acquired in the scope of the European GO Project, with simultaneous acquisition of XBT and CTD (Conductivity-Temperature-Depth) data. The Post-Stack Constrained Impedance Inversion method was used to derive temperature and salinity distributions of seawater and to demonstrate that this method can indeed provide reliable temperature and salinity distribution profiles every 6.25m along the seismic line, with resolutions of 0.16°C and 0.04 psu respectively.

4.1 Inversion method for temperature and salinity

The inversion for temperature and salinity distributions of seawater from combined seismic and oceanographic data is divided into two steps: the first step is the inversion for sound speed or impedance (product of sound speed and density) distribution from combined seismic and oceanographic data, using a post-stack constrained impedance inversion method; the second step is to convert the inverted velocity distribution into temperature and salinity distributions. There are some differences between the application of the wave impedance inversion method in the water layer and conventional impedance inversion in oil and gas exploration. The former needs forward calculations of the variations of the sound speed, density, and impedance from temperature and salinity changes with depth, based on CTD/XBT data and using the sea water state equations (Fofonoff and Millard, 1983).

Post-stack constrained inversion is a relatively mature technique that is widely used in the oil and gas industry in the inversion for geological parameters, and there are several software packages available for this purpose. The inversion method used is model based, and aims to build the best-fitted model to the real seismic data. The initial impedance model is built from seismic data (interpreted seismic horizons) and constraining CTD/XBT data (equivalent to constraining wells in inversion for geology). Each time a synthetic seismogram is derived from the impedance model, the model is adjusted after comparing it with the real seismic data. This procedure is then repeated until a best-fitted model is reached and the final inversion result obtained.

The inversion process consists of the following main steps: (a) importing the CTDs/XBTs and the seismic data; (b) extracting the wavelet from the seismic data using a statistical approach; (c) picking horizons or importing picked horizons; (d) doing CTD/XBT correlation with the seismic data and extracting the wavelet again using the first wavelet estimate from the seismic as the initial guess (sometimes it is also necessary to adjust the depths of the CTD/XBT to get the best correlation with the seismic data); (e) building an initial acoustic impedance model and optimizing to best fit the observations (seismic and CTD/XBT); (f) convert the impedance model into a velocity model, using a density function for the area.

Converting velocity to temperature and salinity is also an important task. This was done by an iterative process, using the empirically derived formula for the relationship between velocity and temperature, salinity and depth (Wilson, 1960):

$$v_p = 1492.9 + 3(T - 10) - 6 \cdot 10^{-3}(T - 10)^2 - 4 \cdot 10^{-2}(T - 18)^2 + 1.2(S - 35) - 10^{-2}(T - 18)(S - 35) + Z / 61$$

Where v_p is the sound speed (m/s), T is temperature (°C), S is salinity (psu), and Z is the depth (m).

The iteration process is as follows: (a) given an initial salinity of 36 psu, the temperature is derived using the formula above; (b) then, the salinity is adjusted according to the T-S relationship for the region, based on CTD casts; (c) the new salinity is introduced in the formula above to get a new temperature; (d) this process is repeated until a convergence in T and S is reached. This approach works because the variation scales of temperature and salinity and the T-S relationship lead to a unique pair of temperature and salinity for a given acoustic velocity. More detailed information on this procedure can be found in Song et al. (2010), Dong (2010) and Huang et al. (2011).

4.2 Application of the inversion method to a case study - the GO data

In 2007, the GO (Geophysical Oceanography) project, briefly described above, carried out a two-month combined seismic and physical oceanography survey in the Gulf of Cadiz, and acquired more than 40 seismic lines (high frequency, intermediate frequency and low frequency), and more than 500 simultaneously XBT measurements and 43 CTDs (Hobbs et al., 2009; http://www.dur.ac.uk/eu.go/general_public/project_info.html). This acquisition campaign was most successful and a wide range of oceanographic features were observed in the study area. This included several Meddies (Mediterranean Outflow eddies).

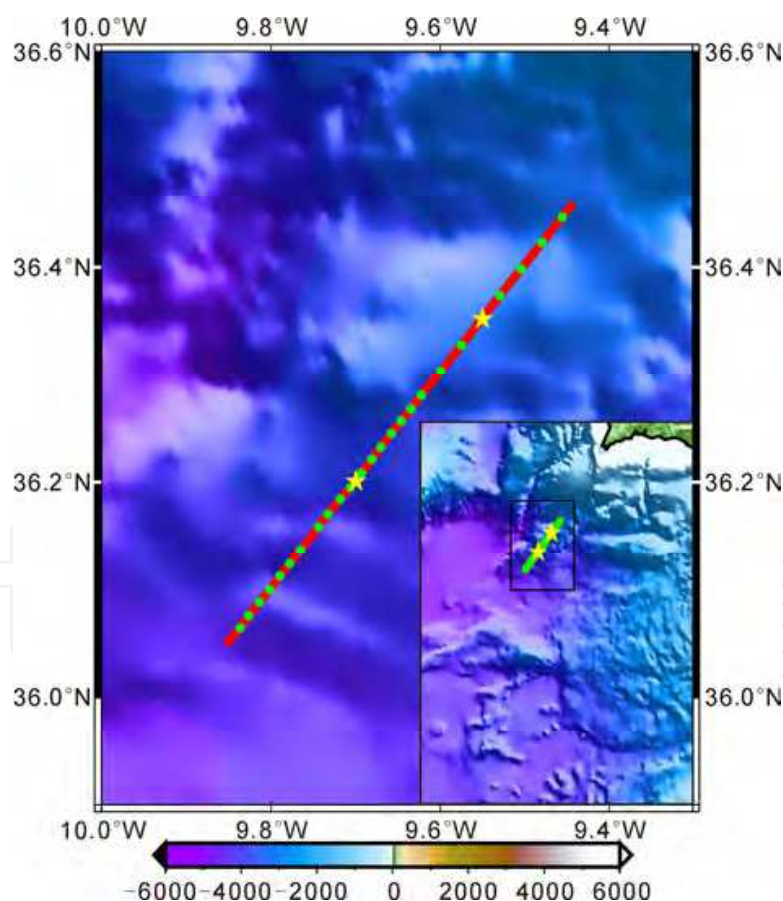


Fig. 7. Location and seafloor topography in the study area, SW of Portugal, with the location of the seismic line GOLR-12, and of the XBT and CTD positions. The red line represents the seismic line, the green solid points represent XBT measurements, and the yellow stars represent CTD locations.

These meddies detach from the main vein of the Mediterranean Outflow (the warm and saline seawater that spills out of Mediterranean from the Strait of Gibraltar and flows along the south margin of Iberian Peninsula) as it passes near the Portimão Canyon and other bathymetric features, and drift away from the continental slope at the depth of neutral buoyancy.

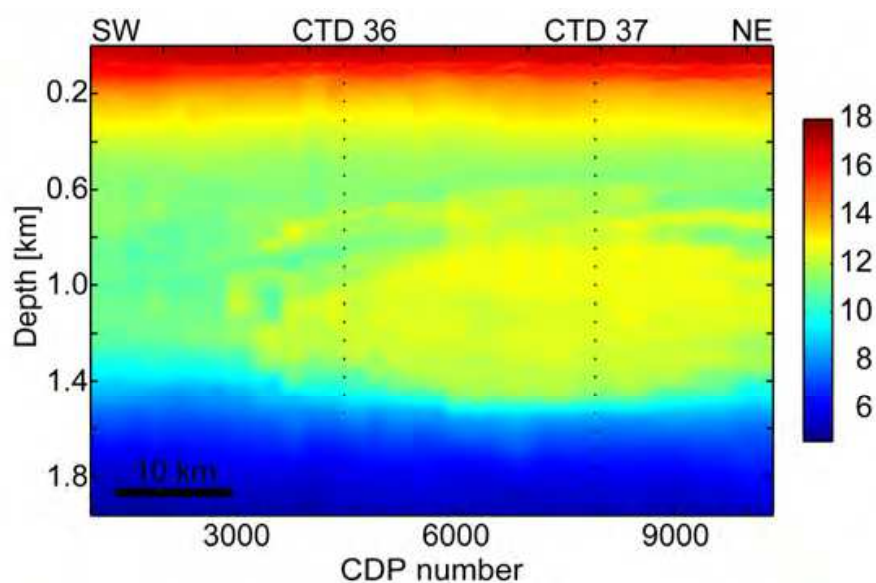


Fig. 8. Inverted temperature distribution for the seismic line GOLR-12. Dot lines represent CTD locations.

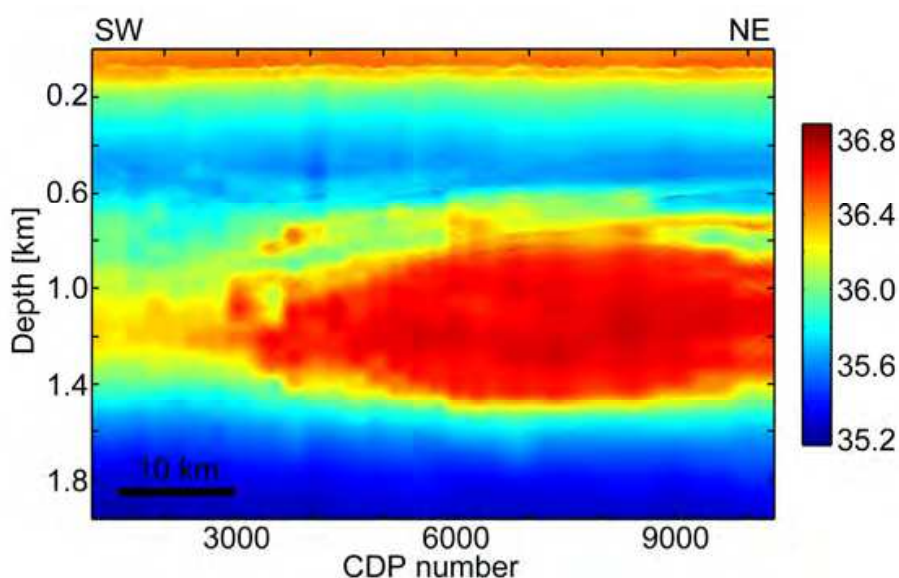


Fig. 9. Inverted salinity distribution for the seismic line GOLR-12.

Here we show results of the inversion of one of the acquired low frequency seismic lines (Line GOLR-12), which was kindly made available for this study (courtesy Dirk Klaeschen and Richard Hobbs). The acquisition parameters for this seismic line were: (a) seismic source: a 1500L BOLT air-guns system with a main frequency band of 5-60 Hz, towed at a

depth of 11m; (b) shot interval: 37.5m; (c) receiver: a 2400 m long SERCEL streamer, towed 8 m below the sea surface, with 192 traces (12.5 m spacing); (d) near offset: 84 m. 24 XBT and 2 CTD profiles were acquired simultaneously and the XBT data was used to constrain in the inversion procedure. Locations of the seismic line, XBTs and CTDs are depicted in Figure 7. After applying the inversion method described above to the seismic line, we got the inverted sections for temperature and salinity depicted in Figures 8 and 9, respectively (Huang et al., 2011). These sections show an elliptical region with the temperatures and salinities characteristic of the warm and saline Mediterranean outflow water, and therefore this elliptical structure can be interpreted as a meddy. Many fine structures can be detected at the boundary of the meddy, and the associated large temperature and salinity gradients indicate strong material and energy interactions. In contrast, the temperature and salinity internal structures within the meddy are far more homogeneous, although some fine structure associated with small variations of these parameters can nevertheless be observed.

Figures 10 and 11 show the comparison of the XBT-measured temperature and XBT-derived salinity using the T-S relationship, with the corresponding inverted values. As can be seen from these figures, a better agreement is achieved in the low frequency components than in the high frequency components. Quantitatively calculated results indicate that mean square errors of temperature and salinity are 0.16°C and 0.04psu respectively. Taking into account the normal variation ranges of these parameters, the inversion result for temperature is better than that for salinity, which is acceptable, because previous studies have shown that the relative contribution of salinity contrasts to reflectivity is approximately 20% (Sallares et al., 2009), i.e. far less than of the contribution from temperature (reflectivity is fairly insensitive to salinity change). The fact that the salinity values used for the inversion were derived from the T-S relationship and not measured by CTDs also certainly affected the inversion results.

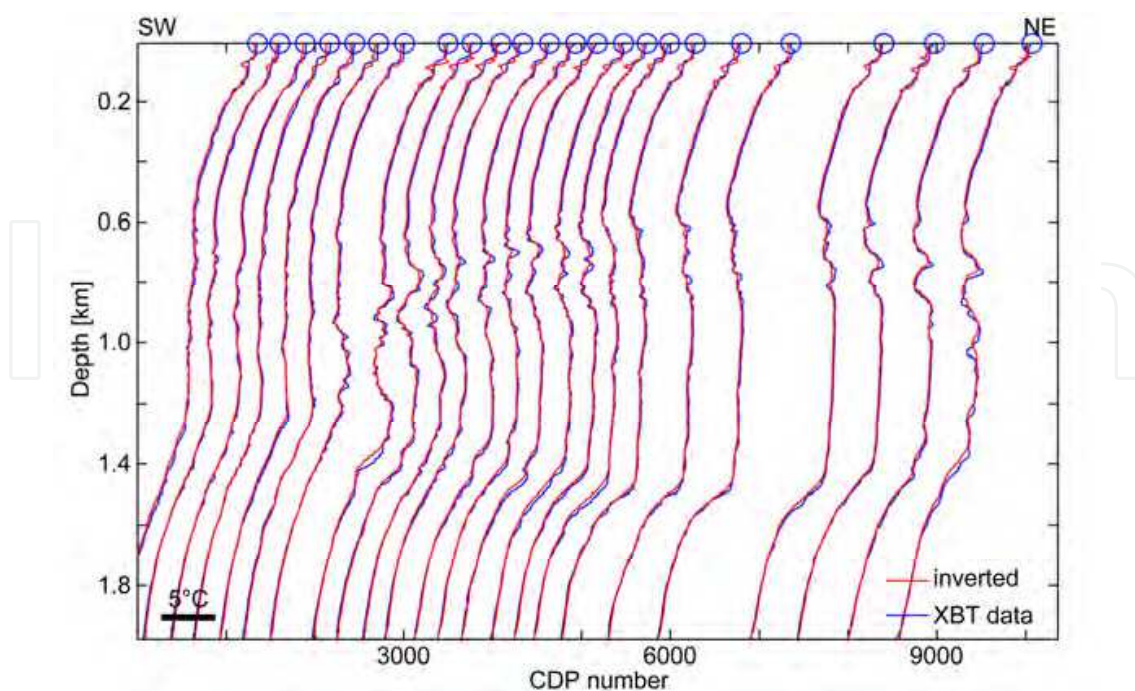


Fig. 10. Inverted and XBT temperature distribution. Blue lines represent XBT data; red lines represent inverted data.

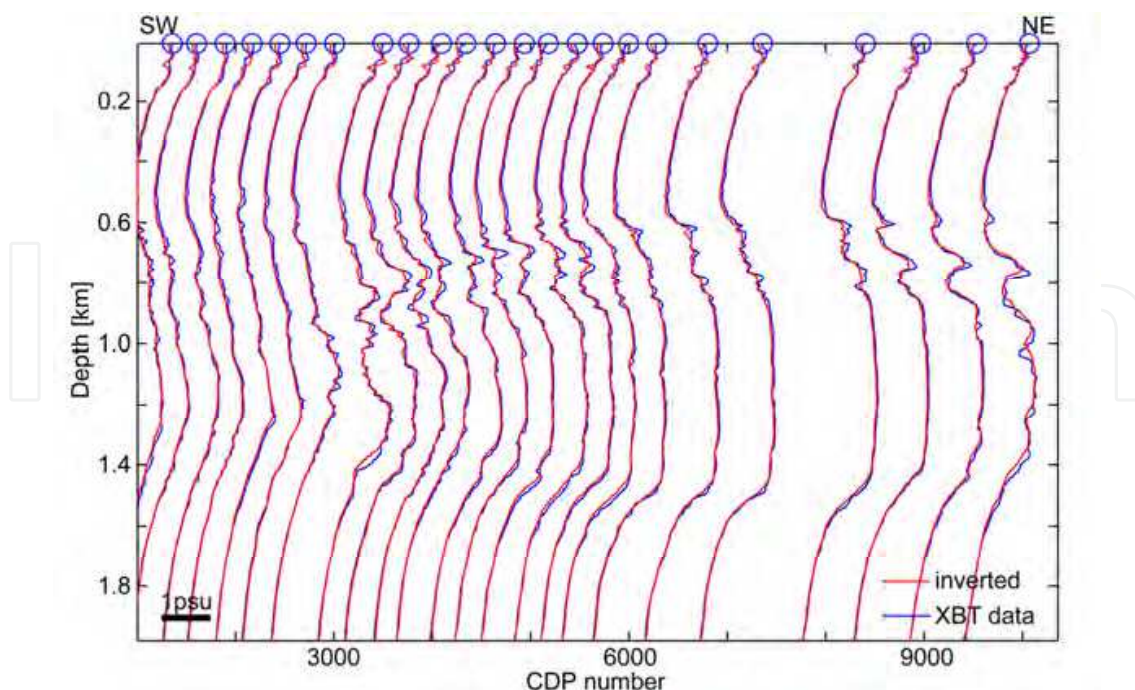


Fig. 11. Inverted and XBT-derived salinity distribution. Blue lines represent XBT-derived data from the temperature and salinity relationship; red lines represent inverted data.

In summary, from the comparisons of the measured and inverted data, we can see that although inversion results can represent detailed temperature and salinity distributions and thermohaline fine structures very well, some errors are nevertheless always inevitable. First, the seismic data processing flows may introduce some errors, since the removal of the direct wave and filtering have some effects on the amplitude and shape of signal. Also, there are always some inaccuracies in the velocity model derived from the acoustic inversion due to the process itself and to noise in the data. It should be also noted that, in the region of strong water mass interaction, the T-S relationship is more complex than the one used here, which is basically an average, and therefore highly accurate results are very difficult to achieve. Finally, the main frequency of the seismic data used is so low and therefore fine structures with the scale less than 15m cannot be detected.

Comparing currently published inversion results, the temperature and salinity inversion resolutions of Papenberg et al. (2010) are 0.1°C and 0.1psu respectively, and those presented here, from Huang et al. (2011) are 0.16°C and 0.04psu. It should be noticed that in their method to derive temperature and salinity, Papenberg et al. (2010) used the inversion result from the seismic data for the high frequency component and the XBT-derived information for low frequency component; hence, their inversion errors are very close to the high frequency component inverted from the seismic data, and the higher resolution can be explained. In summary, the results obtained from combined seismic and oceanographic data inversion using a post-stack constrained impedance inversion method are consistent with the observed XBT data and information derived from them. With the constraints of the seismic data it is possible to achieve high inversion resolution for temperature and salinity in the area between XBTs and with this method it is possible to obtain reliable temperature and salinity distribution profiles every 6.25m along the seismic line, which can be used for analysis on small scale oceanographic features.

5. Conclusions

Physical oceanographic research is based on a large amount of observational data. Mesoscale and small scale thermohaline fine structures are very difficult to be observed using the conventional observation methods because of their low lateral resolution and long observation time. Seismic oceanography makes up for these deficiencies, and makes it possible to obtain fast imaging of a large research area with high lateral resolution; if this acquisition is complemented with simultaneous conventional physical oceanographic measurements such as XBTs or CTDs, the seismic data can be inverted to temperature and salinity with high lateral and reasonably good vertical resolution (although lower than with conventional CTD/XBT measurements). In its early stage, seismic oceanography was mostly used for discriminating seawater boundaries in the ocean and they have been shown to be smoothed images of temperature gradients.

As shown above, two-dimensional temperature and salinity structure sections, with a high lateral resolution, can be obtained from seismic data by using CTD/XBT-controlled seawater wave impedance inversion. The application of this method to the low frequency seismic data of GOLR12, combined with simultaneously acquired XBT and CTD data, derived temperature and salinity distributions of seawater with resolutions of 0.16°C and 0.04psu respectively which demonstrate that seismic data can be used to extract two dimensional temperature and salinity distributions, and hence provide high lateral resolution data for physical oceanographic research. Although the inversion result is affected by the quality of seismic data, data processing and the complexity of the thermohaline mesoscale and fine structures in research area, it can be anticipated that with its development, seismic oceanography will play in the near future a more and more important role in physical oceanographic research.

Besides these post-stack inversion studies, studies have also been carried out to invert physical parameter contrasts from the north-eastern South China Sea, using the AVO (Amplitude Vesus Offset) technique (Dong, 2010), and also to invert seismic data from the same area and obtain the 1D velocity structure of seawater at three CMP (Common Mid-Points) locations, using full waveform inversion (Dong, 2010). Also, a new technique is being developed to explore the 2D thermohaline structure of seawater based on a hybrid inversion method using both pre and post-stack seismic data (Dong, 2010), which should help to solve the problem of the lack of constraints of simultaneous thermohaline data for seismic data.

As shown here and also by Papenberg et al. (2010), thermohaline structure sections with high lateral resolution can be obtained from seismic inversion of multichannel seismic reflection data, constrained by a few CTD/XBT data. This method therefore is highly complementary to conventional physical oceanographic measurements and can overcome some of the difficulties with the conventional measurement methods used in physical oceanography, in particular those concerning the low lateral resolution with high penetration, and can provide vast high resolution oceanographic data for ocean science studies. As a final remark, it should be noted that the inversion studies for the thermohaline structure carried out until present are still preliminary and continued research in this field is expected to provide more accurate determinations in the near future.

6. Acknowledgment

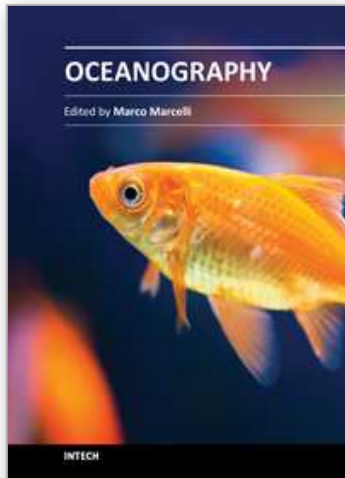
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7. References

- Banda, E., Torné, M. and the Iberian Atlantic Margins Group. (1995). Iberian Atlantic Margins Group investigates deep structure of ocean basins. *EOS, Trans. Am. Geophys. Union*, 76(3), 25, 28–29.
- Biescas, B., Sallarès, V., Pelegrí, J. L., Machín, F., Carbonell, R., Buffett, G., Dañobeitia, J. J., Calahorrano, A. (2008). Imaging meddy finestructure using multichannel seismic reflection data. *Geophysical Research Letters*, 35, L11609.
- Blacic, T. M., Holbrook, W. S. (2009). First images and orientation of internal waves from a 3-D seismic oceanography data set. *Ocean Sci. Discuss.*, 6, 2341–2356.
- Dong, C. Z., Song, H. B., Hao, T. Y., Chen, L., Song, Y. (2009). Studying of oceanic internal wave spectra in the Northeast South China Sea from seismic reflections. *Chinese J. Geophys.* (in Chinese), 52(8), 2050-2055.
- Dong, C. Z. (2010). Seismic oceanography research on inversion of sea-water thermohaline structure and internal waves in South China Sea. Ph.D thesis, Institute of Geology and Geophysics, Chinese Academy of Sciences. 128 pp.
- Fofonoff, N. P., Millard, Jr. R. C. (1983). Algorithms for computation of fundamental properties of seawater, Tech. Pap. Mar. Sci. 44, UNESCO, Paris.
- Gonella, J., et Michon D. (1988). Ondes internes profondes révélées par sismique réflexion au sein des masses d'eau en Atlantique-Est. *Comptes Rendus Acad. Sci. Paris*, T. 306, 781-787.
- Hobbs, R. W., Klaeschen, D., Sallarès, V., Vsemirnova, E., Papenberg, C. (2009). Effect of seismic source bandwidth on reflection sections to image water structure, *Geophys. Res. Lett.*, 2009, 36.
- Holbrook, W. S., Fer, I. (2005). Ocean internal wave spectra inferred from seismic reflection transects. *Geophys Res Lett*, 2005, 32, L15604, doi:10.1029/2005GL023733
- Holbrook, W. S., Páramo, P., Pearse, S., Schmitt, R. W. (2003). Thermohaline fine structure in an oceanographic front from seismic reflection profiling. *Science*, 301, 821-824
- Huang, X. H., Song, H. B., Pinheiro, L. M., Bai, Y. (2011). Ocean temperature and salinity distributions inverted from combined reflection seismic and hydrographic data. *Chinese J. Geophys.* (in Chinese), 2011, 54(5), 1293-1300.
- Klaeschen, D., Hobbs, R. W., Krahmman, G., C. Papenberg, and E. Vsemirnova. (2009). Estimating movement of reflectors in the water column using seismic oceanography. *Geophys. Res. Lett.*, 36, L00D03, doi:10.1029/2009GL038973.
- Krahmann, G., Brandt, P., Klaeschen, D., Reston, T. J.. (2008). Mid-depth internal wave energy off the Iberian Peninsula estimated from seismic reflection data. *Journal of Geophysical Research*, 113, C12016, doi:10.1029/2007JC004678.
- Nakamura, Y., Noguchi, T., Tsuji, T., Itoh, S., Niino, H., Matsuoka, T. (2006). Simultaneous seismic reflection and physical oceanographic observations of oceanic fine structure in the Kuroshio extension front. *Geophys. Res. Lett.*, 33, L23605, doi:10.1029/2006GL027437

- Nandi, P., Holbrook, W. S., Pearse, S., Paramo, P., Schmitt, R. W. (2004). Seismic reflection imaging of water mass boundaries in the Norwegian Sea. *Geophys. Res. Lett.*, 31, L23311, doi:10.1029/2004GL021325
- Papenberg, C., Klaeschen, D., Krahnemann, G., Hobbs, R. W. (2010). Ocean temperature and salinity inverted from combined hydrographic and seismic data. *Geophys. Res. Lett.*, 37, L04601, doi:10.1029/2009GL042115
- Paramo, P., Holbrook, W. S. (2005). Temperature contrasts in the water column inferred from amplitude-versus-offset analysis of acoustic reflections. *Geophys. Res. Lett.*, 32, L24611, doi:10.1029/2005GL024533
- Pinheiro, L. M., Song, H. B., Ruddick, B., Dubert, J., Ambar, I., Mustafa, K., Bezerra, R. (2010). Detailed 2-D imaging of the Mediterranean outflow and meddies off W Iberia from multichannel seismic data. *Journal of Marine Systems*, 79, 89-100
- Richardson, P. L., Bower, A. S., Zenk, W., (2000). A census of Meddies tracked by floats. *Prog. Oceanogr.*, 45 (2), 209-250.
- Ruddick, B., Song, H. B., Dong, C. Z., Pinheiro L. (2009). Water column seismic images as maps of temperature gradient. *Oceanography*, 22(1), 192-205
- Sallares, V., Biescas, B., Buffett, G., Carbonell, R., Dañobeitia, J. J., Pelegrí, J. L. (2009). Relative contribution of temperature and salinity to ocean acoustic reflectivity. *Geophys. Res. Lett.*, 36, L00D06, doi:10.1029/2009GL040187
- Sheen, K. L., White, N. J., Hobbs, R. W. (2009). Estimating mixing rates from seismic images of oceanic structure. *Geophys. Res. Lett.*, 36, L00D04, doi:10.1029/2009GL040106.
- Sheriff, R.E., Geldart, L. P. (1995). *Exploration Seismology*. Cambridge University Press, Trumpington Street, Cambridge CB2 1RP. Second Edition, 592 pp., ISBN 0-521-46826-4.
- Schmitt, R.W., Nandi, P., Ross, T., Lavery A., Holbrook, S. (2005). Acoustic detection of thermohaline staircases in the ocean and laboratory. *Oceans 2005, Proc. MTS/IEEE*, V. 2, 1052-1055
- Song, H. B., Bai, Y., Dong, C. Z., Song, Y. (2010). A preliminary study of application of Empirical Mode Decomposition method in understanding the features of internal waves in the northeastern South China Sea. *Chinese J. Geophys.* (in Chinese), 53(2), 393-400
- Song, H. B., Pinheiro, L. M., Wang, D. X., Dong, C. Z., Song, Y., Bai, Y. (2009). Seismic images of ocean meso-scale eddies and internal waves. *Chinese J. Geophys.* (in Chinese), 52(11), 2775-2780
- Song, Y., Song, H. B., Chen, L., Dong, C. Z., Huang, X. H. (2010). Study of sea water thermohaline structure inversion from seismic data. *Chinese J. Geophys.* (in Chinese), 53(11) , 2696-2702.
- Tsuji, T., Noguchi, T., Niino, H., Matsuoka, T., Nakamura, Y., Tokuyama, H. (2005). Two-dimensional mapping of fine structures in the Kuroshio Current using seismic reflection data. *Geophys. Res. Lett.*, 32, L14609, doi:10.1029/2005GL023095
- Wilson, W. D. (1960). Equation for the speed of sound in seawater. *J. Acoust. Soc. Am.*, 32, 1357.
- Wood, W. T., Holbrook, W. S., Sen, M. K., Stoffa, P. L. (2008). Full waveform inversion of reflection seismic data for ocean temperature profiles. *Geophys. Res. Lett.*, 35, L04608, doi:10.1029/2007GL032359
- Yilmaz, O. (2001), *Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data*, vol. II, Invest. Geophys., vol. 10, 2nd ed., 2027 pp., Society for Exploration Geophysics, Tulsa, Okla.



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How inappropriate to call this planet Earth when it is quite clearly Ocean (Arthur C. Clarke). Life has been originated in the oceans, human health and activities depend from the oceans and the world life is modulated by marine and oceanic processes. From the micro-scale, like coastal processes, to macro-scale, the oceans, the seas and the marine life, play the main role to maintain the earth equilibrium, both from a physical and a chemical point of view. Since ancient times, the world's oceans discovery has brought to humanity development and wealth of knowledge, the metaphors of Ulysses and Jason, represent the cultural growth gained through the explorations and discoveries. The modern oceanographic research represents one of the last frontier of the knowledge of our planet, it depends on the oceans exploration and so it is strictly connected to the development of new technologies. Furthermore, other scientific and social disciplines can provide many fundamental inputs to complete the description of the entire ocean ecosystem. Such multidisciplinary approach will lead us to understand the better way to preserve our "Blue Planet": the Earth.

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