Revista Brasileira de Geofísica
RBGf
Brazilian Journal of Geophysics

Revista Brasileira de Geofísica (2018) 36(1): 5-17

ISSN 0102-261X
www.scielo.br/rbg

USING SEISMIC DATA FROM THE OIL AND GAS INDUSTRY FOR OCEANOGRAPHIC STRUCTURES DETECTION

Marcus Vinícius Carpes Barão[1], João Paulo Ristow[2], Marina Martins Bousfield[2], Guillaume François Gilbert Barrault[1] and Antonio Henrique da Fontoura Klein[1]

ABSTRACT. This work presents a methodology for legacy seismic data from oil and gas industry use for water column acoustic imaging. The objective is to improve the detection of internal mesoscale ocean structures by combining the results of the seismic data processing with oceanographic parameters. The procedure to obtain these images is called seismic oceanography and is an emerging tool for large-scale analysis of physical properties and processes of the ocean. The seismic data collection from the oil industry can be used to extract seismic oceanographic information since they both have similar survey configuration requirements for their data acquisition. The seismic data used were obtained from the Brazilian Oil Exploration Database and the oceanographic data were obtained from World Ocean Database. The methodology used to detect oceanographic structures was divided into four stages: data selection; oceanographic parameters analysis; seismic oceanography processing and interpretation; and combined analysis of seismic data with oceanographic data. The analysis and interpretation of the data showed that reflectivity curves calculated using oceanographic parameters have strong correlation with the seismic oceanography data. The detected reflections corroborate with the literature information about the boundaries of the water masses of the region and with abrupt gradients of the oceanographic parameters.

Keywords: seismic oceanography, acoustic image, water masses, water column reflections, oceanographic parameters.

RESUMO. Este trabalho apresenta uma metodologia para utilização de dados sísmicos do acervo da indústria de petróleo e gás para gerar imagens acústicas da coluna d'água. O objetivo é melhorar a detecção de estruturas oceânicas em mesoescala por meio da combinação de resultados de processamento de dados sísmicos com parâmetros oceanográficos. Denominada de oceanografia sísmica, o presente método é uma ferramenta emergente para a análise de propriedades físicas e processos dos oceanos. O acervo de dados sísmicos da indústria do petróleo pode ser utilizado para extrair informação sísmica oceanográfica, uma vez que ambos têm configurações semelhantes para a sua aquisição de dados. Os dados sísmicos utilizados foram obtidos na Base de Dados de Exploração e Produção e os dados oceanográficos foram obtidos no World Ocean Database. A metodologia utilizada foi dividida em quatro etapas: seleção de dados; análise de parâmetros oceanográficos; processamento e interpretação da oceanografia sísmica; e análise combinada de dados sísmicos com dados oceanográficos. Resultados mostram que as curvas de refletividade calculadas utilizando parâmetros oceanográficos têm forte correlação com os dados da oceanografia sísmica. As reflexões detectadas corroboraram com as informações da literatura sobre os limites das massas d'água da região e com gradientes abruptos dos parâmetros oceanográficos.

Palavras-chave: oceanografia sísmica, imagem acústica, massas d'água, reflexões na coluna d'água, parâmetros oceanográficos.

[1] Universidade Federal de Santa Catarina, Laboratório de Oceanografia Costeira, Estação Experimental "Prof. Elpídio Beltrame", Barra da Lagoa, Florianópolis, SC, Brazil.
– E-mails: ocmarcusbarao@gmail.com; guillaume.barrault@ufsc.br; ahfklein@gmail.com
[2] Universidade Federal de Santa Catarina, Laboratório de Vibrações e Acústica, Campus Universitário, Trindade, Florianópolis, SC, Brazil.
– E-mails: jpristow@gmail.com; marinambousfield@gmail.com

INTRODUCTION

Seismic oceanography is a recent method that allows investigating the oceanographic structures in a wide range of scales, from mesoscale to submesoscale and finescale, with resolutions of 10 m to 100 m in the vertical and lateral dimensions and along the whole water depth (Nandi et al., 2004; Biescas et al., 2008; Carniel et al., 2012). Thereby resolution – in lateral axis – can be improved by a hundred times in relation to those obtained with conventional techniques. The method can be used to characterize the physics of the ecosystems with an unprecedented resolution, which form a new way to observe the deep ocean and to link it with biological and chemical processes.

In the last 14 years, researchers have shown that seismic oceanography is able to image thermohaline structures such as fronts (Holbrook et al., 2003), eddies (Biescas et al., 2008), overturning circulation (Sheen et al., 2009), undercurrents (Buffett et al., 2009) and internal solitary waves (Tang et al., 2014). The observed reflections in the seismograms are the result of vertical impedance contrasts among the water layers. These contrasts occur, mainly, by variations in sound velocity, which are caused by variations in temperature, salinity and density (Ruddick et al., 2009). An increasing interest topic in seismic oceanography are the inversion methods that allow recovering temperature and salinity data from the acoustic pressure signals, providing 2D maps of these parameters and derived properties with high lateral resolution over large areas in the deep ocean (Papenberg et al., 2010; Biescas et al., 2014). During the last years, this method has also been used to analyze the propagation of waves and energy cascade in the ocean by measuring the spectra of the vertical displacement of seismic reflectors (Holbrook & Fer, 2005; Sallarès et al., 2016).

Blacic & Holbrook (2009) presented the first 3D images of oceanographic structures obtained from oil industry data. Besides being one of the only papers that use oil industry data, the authors highlight the importance of measuring temperature and salinity profiles (and consequently the sound velocity) during the seismic survey to obtain representative results during the inversion process. Regarding the temperature profile, Nandi et al. (2004) validated the notable sensibility of the acoustic reflection at lower frequencies by tiny variations in the temperature, indicating values of 0.03°C. This result was obtained by detailed comparisons between the acoustic reflection and temperature data collected in situ over 172 km in the Norwegian Sea. Fortin & Holbrook (2009) studied the quality requirements of sound velocity values used as input for seismic oceanography processing steps, such as normal moveout (NMO) analysis and post-stack migration. Results indicated the necessity of rigorous, locally derived sound-speed models.

The method also shows potential to be applied in shallow waters. Piété et al. (2013) were able to create high resolution images of shallowest layers of the ocean, using small offsets and a system with multiple streamers and a sparker. The result of this study showed a detailed image of the seasonal thermocline at 30 m depth, in a water column ranging from 50 m to 150 m.

The main difference between the conventional seismic processing and seismic oceanography processing is the data section analyzed. The information in the section that represents the water layer is the focus of seismic oceanography processing. For this reason, it is necessary to apply an important step: the removal of the direct arrival. This effect is present in the first seconds of the seismogram and masks the water mass reflection. Usually, the section of the data related to de surface and subsurface reflection is also removed. The removal of the subsurface reflections changes the dynamic range of the visualization. In other words, data having amplitude outside the range of interest are removed, enabling a better display of the small amplitudes. This step allows to restrict the analysis to the seismic data portion where it was possible to observe the presence of the acoustic signal in consonance with the water column parameters.

Whilst the reflections imaged in the water have amplitudes from 100 to 1000 times weaker than those from the solid Earth, the changes in water parameters are perceptible and the visualization can be improved by the gain in the processing (Fer & Holbrook, 2008).

Regarding the data used, there may be a large difference between the use of legacy data and data from a specific designed survey in seismic oceanography processing. Specific designed surveys have its configurations selected according to the processing objective, as done by Piété et al. (2013). In this case, most reliable results can be obtained and particular studies can be carried out. As drawback, the cost and logistic effort to obtain this kind of data is tremendous. On the other hand, legacy industry data can be obtained with a much less effort, because there is a huge set of onshore and offshore seismic data, which is the result of many years of oil and gas prospecting and exploration. Nonetheless, not all the dataset can be used for seismic oceanography. Some requirements, mostly regarding the survey configuration, must be attended to ensure a representative seismic oceanography data. In this way, the seismic oceanography methodology must be adapted for using Marine Multichannel Seismic (MCS) data of the oil and gas industry.

The main advantage in the use of MCS data acquired by industry comes from the fact that the survey method used in these data is the same required for seismic oceanography processing. In this sense, the historic seismic dataset of oil industry offers an enormous amount of multichannel seismic data that could be used for oceanographic research.

As previously reported by Fortin & Holbrook (2009), the certain knowledge of sound velocity in the water column is required to not damage the signal-to-noise ratio and ensure the quality of the processed seismic images to identify the reflectors.

In historical oceanographic data, it is possible to notice the variability of the results from a great diversity of researches carried out by different objectives and scales frames (Thomson & Emery, 2014). This variability represents a challenge to the reanalyzes focusing in ocean structures in different resolution. The analyses of the oceanography stations used in this paper, for instance, are not efficient enough to analyze the mesoscale structures at the horizontal spatial scales of $O(10^1$ m) and $O(10^3$ m) due to a wide distance between each station ($\approx$ 18 km).

Despite the limitation in the analyzes of the oceanographic and seismic data, they can be combine to bring new information of oceanic structures and a new use for two archived data.

The objective of this work is to improve the detection and visualization of the internal mesoscale ocean structures by combining the analysis and results of the seismic historical data processing with oceanographic parameters obtained by direct oceanographic measurements.

METHODOLOGY

The methodological proceeding for ocean structures detection and interpretation will be divided in four main steps: data selection; oceanographic parameters analysis; seismic oceanography processing and interpretation; and combined analysis of seismic data with oceanographic data. First, a set of seismic data and a set of oceanographic data are selected. The analysis of each dataset will be done individually, in order to create hypothesis for the environment description. The combined analysis is then performed: in this step the oceanographic parameters are converted to acoustical parameters in order to compare it with the reflection image obtained with the seismic oceanography processing. Figure 1 illustrates the basic methodological flowchart.

The seismic data were selected in the Brazilian Oil Exploration Database (BDEP). Preference was given to surveys that use high energy sources (like airguns with volume greater than 2000 inch[3]), since this is one of the limiting parameters for the use of seismic oceanography. Concerning oceanographic parameters, it is preferable that they be acquired together with seismic data. As the majority of seismic data from BDEP database don't have an associated oceanographic dataset, it was obtained from World Ocean Database oceanographic stations. The selected data needed to be as close as possible, spatially and temporally, to the seismic line.

The data from the oceanographic stations was studied in respect to the temperature and salinity. The structures in the water column such as water masses and other events can be identified by changes in the profiles of these parameters. A comparison between the temperature and salinity gradients and a TS diagram could be done aiming the data interpretation.

The seismic line was processed seeking to analyze only the water column portion. The seismic oceanography processing was performed using Seismic Unix software and consisted in seven main steps (Yilmaz, 2001): (1) pre-processing, which starts after the data is converted to the software format and consist in: insertion of the geometry of the survey, removal of bad traces, frequency filtering and amplitude correction due to spherical divergence; (2) application of an adaptive subtraction to remove the direct wave from the source; (3) velocity analysis to determine an approximation of the sound velocity field in the water column, performed on Common Depth Point (CDP) gathers; (4) the normal moveout correction of CDP gathers with the velocity field; (5) stacking of the CDP traces with offsets larger than 300 m; (6) removal of the subsurface reflections; and (7) time to depth conversion to determine the spatial location of the processed seismic section. The second to meters conversion can be done by the simple relation

$$z = c * \frac{t}{2}, \qquad (1)$$

where z is the depth, c is the estimated sound velocity and t is the two-way travel time. Detailed information regarding the processing steps of the seismic oceanography can be found in Biescas et al. (2008).

The resulting seismic image of the water column portion was analyzed and investigated to find reflection events that could be related to the expected oceanographic structures and processes of the studied region.

By combining the seismic image result with the oceanographic parameters obtained at the oceanographic stations, the interpretation of the investigated area can be improved. To perform a combined analysis, it was first necessary to establish acoustic parameters – as sound velocity and sound reflectivity – of the water column based on the oceanographic parameters.

The sound velocity was calculated using the TEOS-10[3] (IOC,

[3]Thermodynamic Equation Of Seawater (TEOS) adopted by the Intergovernmental Oceanographic Commission, from which all properties of seawater such as density, enthalpy, entropy sound velocity and others can be derived.

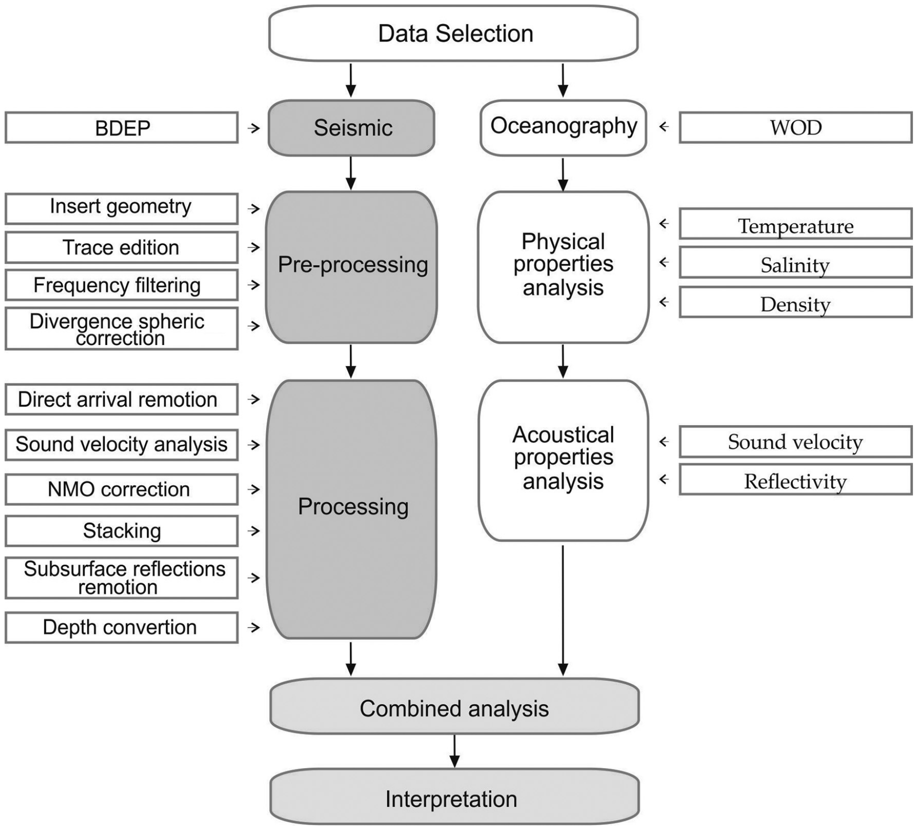

Figure 1 – Processing methodology of the seismic and oceanographic data.

SCOR and IAPSO, 2010). The Ocean Data View (ODV) software was used, since it already has the TEOS-10 implemented. For sound velocity calculation the density magnitude was needed, which was calculated according to Fofonoff & Millard (1983).

The reflectivity of the water column was compared with the seismic reflections highlighted with the seismic oceanography processing steps. The reflectivity (R_p) of the media could be approximated by the product of sound velocity and density and could be obtained by the relation

$$R_p = \frac{1}{c}\frac{dc}{dz} + \frac{1}{\rho}\frac{d\rho}{dz}, \qquad (2)$$

where c is the sound velocity, ρ is the density and z is the depth.

Lastly, the interpretation of the combined analysis was performed. In this step, the main acoustic reflections were highlighted and intuitively correlated to the ocean events or processes that may have generated it. Therefore, the main reflection events are compared to the reflectivity profile that could be related to the oceanographic structures.

DATA SELECTION AND ENVIRONMENT CHARACTERIZATION

The industrial multichannel seismic data used in this work were obtained in the oceanic region of Santa Catarina, in front of Florianópolis Island, Brazil. It corresponds to 0247_Caravela_1993 line and was acquired from 27.46° S to 27.71° S and 47.32° W to 46.95° W[4] in January 1st, 1993.

To obtain the information about salinity and temperature, were selected data from stations near to the seismic line with a time gap of 30 days. Five oceanographic stations have been used to obtain those parameters. The oceanographic data were recorded using a CTD from the METEOR vessel in the project World Ocean Circulation Experiment (WOCE) in January 31st, 1993, that were obtained from the World Ocean Database (Boyer et al., 2013)[5]. The acquisition coordinates are 27.68° S to 27.90° S and 47.39° W to 46.67° W. Figure 2 shows the global position of the seismic line and location of the five stations that provided the oceanographic data used.

[4] The data were kindly provided by the Brazilian National Petroleum Agency (ANP).

[5] World Ocean Database cruise Reference DE009626 (https://www.nodc.noaa.gov/OC5/SELECT/allcruises/DE009626.html).

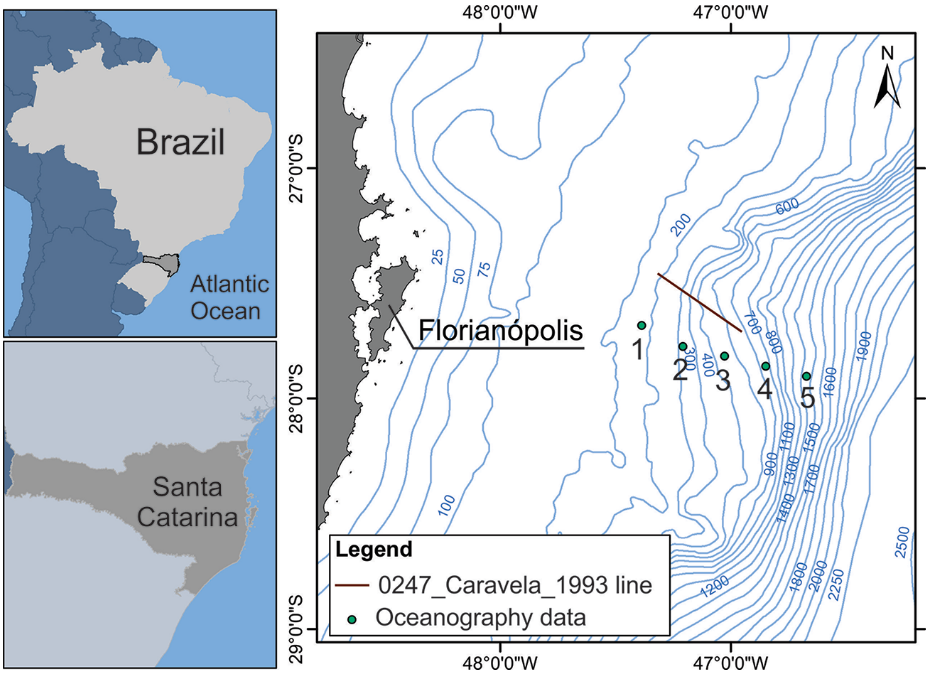

Figure 2 – Map of the studied area. The red line indicates the seismic line position acquired in January 1st, 1993. The dots indicate the oceanographic stations location selected in WOD, acquired in January 31st, 1993. The Geographic Coordinate System and Datum used was SIRGAS 2000.

The time gap of 30 days between the survey and the oceanographic profiles do not allow to recover the temperature and salinity with confidence through the inversion data processing due to dynamical processes in the water column. However, this interval of analysis is able to recover structural information of the mesoscale process.

Although they are not collected concomitantly, data from oceanographic stations still contain information on mesostructure since the temporal scale of these events varies from few days to a year (Lampitt et al., 2010). This fact proves the viability to analyze the seismic and oceanographic data in this region, even with a thirty-day interval.

Notwithstanding the limitation to apply the inversion data processing in this study, the seismic oceanography analysis allows to extract synoptic visualization of features in the water column and to associate them with oceanographic parameters.

Several studies were already conducted to characterize this environment in oceanographic terms (Campos et al., 1995; Da Silveira et al., 2000; Silva, 2006). The known water masses present in this region are the Tropical Water (TW), the South Atlantic Central Water (SACW) and the Antarctic Intermediate Water (AAIW). The TW and SACW flow southwards carried by the Brazil Current (BC), western boundary current associate to subtropical gyre of South Atlantic. In contrast the movement of previous water masses, the AAIW has distinct directions according the latitude where it is located. Described by Müller et al. (1998) and corroborate by Stramma & England (1999), the AAIW reaches the Brazilian continental margin from the east as part of the South Atlantic Subtropical Gyre, showing a spreading northward at 25°S and southward at 28°S. According to Biló et al. (2014) and Lengeais et al. (2013), the axis of bifurcation is denominated Santos Bifurcation and is located at 27°S, approximately.

Southward this bifurcation, the BC thickens from 350 m at 22.7°S to 850 m at 27.9°S by carrying out the AAIW (Lengeais et al., 2013; Biló et al., 2014).

A TS diagram[6] was constructed to corroborate the oceanographic data with the literature information, which is shown in Figure 3. The colorful dots represent the temperature and salinity values measured by the five stations. The color of each dot represents the depth associated with it, according to the depth scale. Magenta circles represent the most representative values of temperature and salinity related to each water mass according to the literature (Silva, 2006).

It can be seen the color dots are sorted according the three water masses: TW, SACW and AAIW, taking into account the information on the literature on the characteristic waters. The dots

[6]Diagram relating the measured salinity and temperature in a season.

that are closer to the magenta circles indicate the core of each water mass and the dots sorted among the points represent the transient region of parameters between two water masses (Thomson & Emery, 2014). It can be seen that a large amount of dots is located between the SACW and the TW masses, representing a volumetric mixing layer between them.

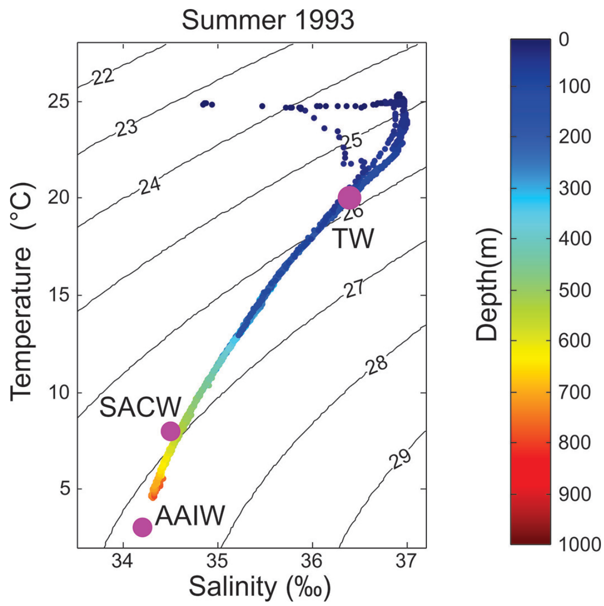

Figure 3 – TS diagram of the oceanographic data obtained at the stations in summer of 1993.

As noted by Campos et al. (1995) and Da Silveira et al. (2000), the distribution of points as observed in the obtained TS diagram corroborates with what is expected for the water masses and the water dynamics of the Southwest Atlantic region and confirm the presence of the three expected water masses, like registered in the literature.

The Tropical Water (TW) is in the shallow region of the water column and can reach up to 200 m deep. The temperature and salinity indexes are up to 20°C and 36‰, respectively (Da Silveira et al., 2000). This water mass has a shallow layer of mixing, whose length is above 50 m and 90 m. The second mass encountered in the region is the South Atlantic Central Water (SACW), located just below the TW and reaching up to 700 m deep. It is characterized by temperatures between 6°C and 20°C and salinity ranges from 34.6‰ to 36‰ (Da Silveira et al., 2000). Finally, the third water mass – which is limited by the SACW and can reach up to 1500 m deep – is the Antarctic Intermediate Water (AAIW), which is identified by temperatures between 3°C and 6°C and salinity ranges from 34.20‰ to 34.60‰ (Da Silveira et al., 2000).

Figure 3 also shows that the main water mass in the studied region is the SACW, which covers the majority part of the analyzed portion of the water column. Its boundaries mark the transition with the TW at the upper part and with the AAIW at the lower part. The boundaries positions of the SACW, nonetheless, are not well defined and vary depending on the author. Some documented upper and lower boundaries of the SACW according the literature are presented in Table 1.

Table 1 – Upper and lower boundaries of SACW mass according the literature for the Southwest Brazilian oceanic region.

Authors	SACW mass Boundaries	
	Upper	Lower
Silva (2006)	177.0 m	603.0 m
Da Silveira et al. (2000)	400.0 m	700.0 m
Campos et al. (1995)	200.0 m	750.0 m
Reference Values		
Depth	259.0 m	684.4 m
Uncertainty	±122.6 m	±74.6 m

In order to have reference depth values for the upper and lower boundaries of the SACW mass, the mean of the values found in the literature was used. The uncertainties of these depth values were calculated using the standard deviation of the depth values. These statistical quantities are shown in the lower part of Table 1, and will be used in the seismic and oceanographic data analysis in the next section.

RESULTS AND DISCUSSION

Oceanographic Parameters

Temperature and salinity information from the five studied stations in the summer of 1993 are reported in Figure 4. The first and second stations present different patterns in relation to the others for the first 50 m of water column. This can be explained by their location in shallow waters, which make them influenced by coastal waters.

The curves can be roughly divided in three regions with different behaviors: the surface up to 50 m; the center, with depth varying from 50 m to 470 m; and the bottom, located underneath the last one. These regions, though, are not related to the depths of the water masses boundaries, as can be seen in the SACW boundaries showed in Figure 4. This lack of information regarding the water masses can be associated with a presence of a large transient layer between them, which makes difficult the localization of specific water masses.

In all stations, the temperature profile shows nearly constant values of 25°C on the first 50 meters. This behavior is known and related to the presence of a mixing layer in the first meters

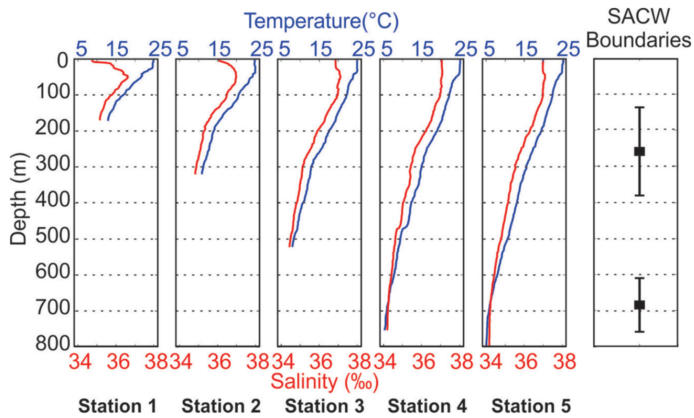

Figure 4 – Temperature and salinity profiles at oceanographic stations obtained from World Ocean Database for the summer of 1993 at Santa Catarina shelf break.

of the water column. Just below this depth, there is a strong gradient where the temperature could vary up to 4°C and decrease gradually with depth until reach the seabed. Regarding the regions which present substantial contrasts, it is possible to cite station 4 where is noticed a 2°C variation at 470 m depth and station 3 where is noticed a 1°C contrasts at 240 m, 290 m, 320 m and 480 m depth. These variations can be related to a mixing process between TW and SACW located in the lower portions, but the absence of extra data hinders further conclusions.

Regarding salinity, it tends to increase with the depth on the first 50 meters in all the stations, reaching values of 37.2‰. Underneath this depth, salinity presents the same pattern as the temperature, decreasing gradually with depth until reach de seabed. Station 4 showed again a strong gradient, of 0.4‰ at 470 m depth, which is probably caused by the same event that created the abrupt temperature gradient.

It is noticeable that temperature and salinity single curves are not able to detect structures in the water column or explain the high gradients found in some depths. This occurs mainly due to the relative low spatial sampling of the analyzed oceanography station (≈18 km), decreasing the lateral detection of oceanographic mesoscale structures. This fact does not allow to establish correlations between gradients in different profiles.

The spatial sampling problem, however, can be bypassed by means of the seismic oceanography processing and analysis, which can map events with resolution of hundreds of meters because of the continuous acquisition.

Seismic Oceanography

The processing methodology of seismic oceanography was applied to 1712 acquired shots, resulting in 2820 common depth points (CDPs) profiles along 45.7 km.

After the stacking process, it was possible to notice an improvement in the visualization of the reflections in the traces, since this step improves the signal to noise ratio of the data. In the next step, the reflections generated by the sound interaction with the ocean floor were removed. The removed seafloor reflections can mask the water column events generated once its amplitude can be hundreds to thousands times higher than the reflections on the water (Holbrook & Fer, 2005).

The seismic processing allowed observing reflectors in 38 km of the whole line which corresponds to the region of the water column in the shelf break between 270 m and 650 m depth. The reflectors have undulations patterns between 320 m and 550 m depth and continuity around 1000 m. Figure 5 shows the image result of the seismic oceanography processing.

The right box in Figure 5 shows the statistical values (mean depth and uncertainty) of the upper and lower boundaries of the SACW. It can be seen that the majority of the imaged section of the water column corresponds to the SACW mass. The dashed lines in the Figure 5 represent the projection of the oceanographic stations positions in the longitude axis plotted over the seismic line. However, the actual distance among stations 2, 3, 4 and its projection in the seismogram are 26.46 km, 17.72 km and 19.63 km respectively, as shown in Figure 2. Although the spatial and temporal differences between oceanographic and seismic data, the combination of the information allow us to establish a qualitative comparison between the two data types.

The absence of acoustic reflections in the shallow regions (less than 270 m depth) is related to the acquisition geometry. The distance between the source and the receptor (offset) affect directly the data, creating an inhibit zone, where the reflections in the water layer are not recorded and a lack of information can be

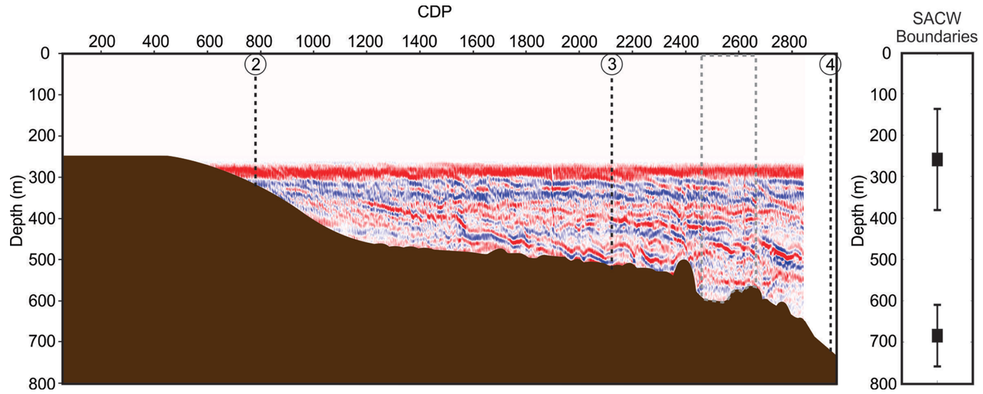

Figure 5 – Result of seismic oceanography processing of the 0247_Caravela_93 line. The dashed lines represent the location projection of the near oceanographic stations.

noted. After this zone occur the direct path arrivals, which are removed during the seismic data processing. The red constant line near the 300 m depth present that can be noted in Figure 5 is an effect of the removal of this direct wave record.

Due to the lack of correlated reflections over the CDPs in the depths of the SACW mean boundary, is possible to affirm that the seismogram is not able to identify the transition layers among the water masses.

In this way, the reflections displayed in Figure 5 are related to other events than strictly to water masses limits. These events can be associated to turbulent flow and mixing process inside the SACW, connected to the transport close to the ocean bottom and the interaction with the lower boundary of the TW, respectively.

Figure 6 shows the interpreted seismic oceanography result. The main reflections present in Figure 5 are highlighted and divided in two regions. The first region (A), close to the ocean bottom, shows an adjustment according to the variation of ocean topography, represented by steepness pattern of the deep reflections. This reflection pattern indicates an interaction between the water mass movement and the ocean topography. The second region (B) represents the center of water column. In this region, the reflections have reduced inclination and vertical displacement when compared to the reflections of region A.

The undulation pattern presented in reflections of both regions A and B are similar to the ones described by Biescas et al. (2014) and Mojica (2015), which confirms these forms through models of signal propagation in layers with different distributions of temperature and salinity.

The reflection information obtained with the seismic oceanography processing allows the investigation of water column with lateral sampling near to 13 m, which enables the detection of structures that oceanographic station data may not be capable to detect, because of it spaced sampling. Despite offering more trustworthy information, the oceanographic parameters have limited resolution due to the large distance among the stations. The lateral sub-sampling of temperature and salinity inhibits a robust detection of structures smaller than its spatial sampling which makes difficult the characterization of the environment. The combined analysis of the direct oceanographic data and seismic data aims to offers reliability of the oceanographic parameters and dynamics analysis with the resolution of the seismic oceanography processing.

COMBINED ANALYSIS

The first step to correlate the results of seismic oceanography with the oceanographic parameters is the calculation of the acoustical parameters related to the oceanographic ones. The seismic oceanography results are based on the reflectivity of the water column, and reflectivity, in turn, is dependent of water density and sound velocity.

Density and sound velocity along the water column were estimated using temperature and salinity of the five oceanographic stations. The results, reported in Figure 7, showed constant patterns for density and sound velocity for the first 50 m depth with values of 1024.7 kg/m^3 and 1537 m/s, respectively. An exception could be noted for the density registered at the first and second stations.

At 470 m depth, at station 4, it is noticeable variations of 0.2 kg/m^3 and 10 m/s, due to the strong gradient of temperature and salinity in this region.

The reflectivity profiles of each station were estimated using the previous density and sound velocity profiles. The results are shown in Figure 8.

The reflectivity profiles show variations in the amplitude over

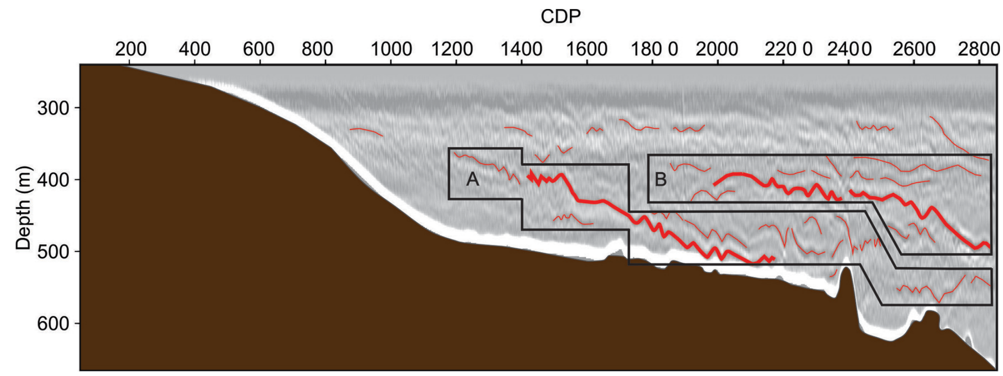

Figure 6 – Seismogram with the main reflections highlighted and divided in two groups: The deeper reflections result by the water mass interaction with the ocean topography (A) and the reflections in the center of the water column, result by the water masses mixing (B).

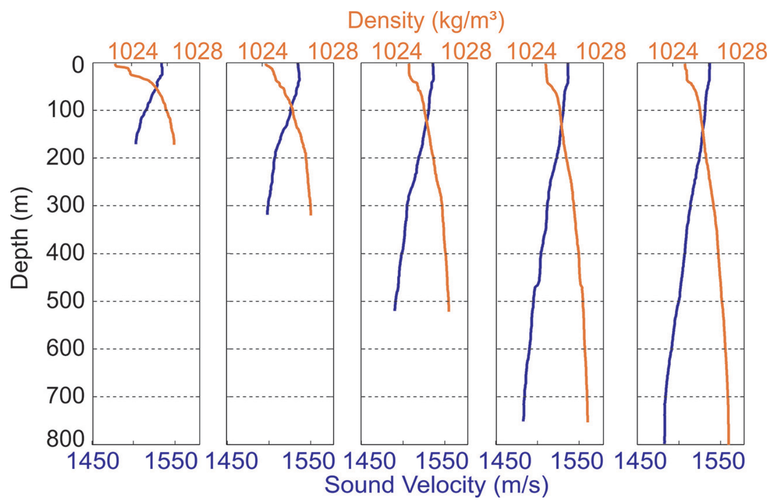

Figure 7 – Density and sound velocity profiles at oceanographic stations obtained by temperature and salinity data from World Ocean Database for the summer of 1993.

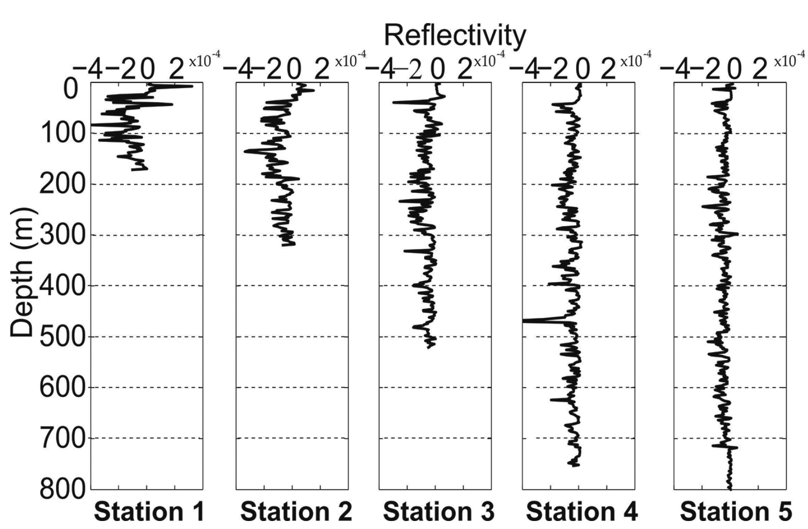

Figure 8 – Reflectivity profiles at oceanographic stations obtained by temperature and salinity data from World Ocean Database for the summer of 1993.

the whole water column. However, it is possible to remark that regions which showed strong temperature and salinity gradients also presented high reflectivity values. The peaks in the reflectivity profiles are distributed over the region between the surface and center regions at all the stations. Remarkable peaks are located in 240 m, 290 m, 320 m and 480 m depth at station 3 and in 470 m depth at station 4. Those peaks in the estimated reflectivity are responsible for the reflections in the water that are recorded in the seismic oceanography data.

The high reflectivity values are located in areas with considerable variation of the temperature and salinity, e.g. bellow the shallow mixed layer at 50 m depth. However, there are other points in the reflectivity profile which are out of the water masses boundary, e.g. the peak of the reflectivity at 470 m depth in station 4.

Although there is a smooth transition of water masses as showed in the oceanographic analysis, it was observed a trend of peaks of reflectivity towards the shallow waters. The peaks started in 710 m depth at station 5, kept rising in 470 m depth at station 4 and finished in 320 m depth at station 3. All these peaks are located whit in the SACW.

The smooth behavior of the reflectivity profile at station 5 beneath 710 m depth was associated to the presence of the AAIW mass. This depth is coherent with the values encountered in the literature and with the statistical values used in this work. This smooth behavior of reflectivity is caused by the homogeneity of the Antarctic waters (Da Silveira et al., 2000). The absence of this kind of behavior in the other stations indicates that this mass is only found deep waters and is not present in the analyzed region using seismic oceanography.

The SACW layer presents no high gradients of temperature and salinity. This characteristic results in reduced gradients of sound velocity, and thus, generates low amplitudes reflections when compared with geologic ones. This occurs due to the presence of a transition zone between the two water masses, which can reach dozens of meters.

Even though the acquisitions of the oceanographic station and seismic data were not simultaneous, the comparison between them offered a good way to relate the data, highlighting the corroboration between reflectors and the region with high reflectivity (Fig. 9).

This seismogram and the station 4 are spatially separated by 19.63 km and temporally separated by 30 days. In Figure 9, the correspondence between the reflections in the water column from seismic data and the reflectance generated by the gradient of impedance in the physical profiles is observed. The reflections events at 350 m and 550 m deep in Figures 9(a) and 9(b), located in the B group, represents the events inside the SACW mass, following the trend observed in stations 3, 4 and 5. At the same depths can be recognized events with high sound velocity gradients in Figure 9(d). These gradients result in high values of reflectivity, as can be seen in Figure 9(c).

A rising trend was observed in the oceanographic stations 3, 4 and 5 data for reflectivity. This trend was also detected in the reflections registered at the seismogram. This fact confirms the relative stratification at this region in the summer of 1993 (Fig. 10).

CONCLUSION

This work shows that seismic oceanography can contribute to the improvement of the oceanography knowledge of a region. The seismic oceanography processing of the 0247_Caravela_1993 seismic line was able to evidence the water column reflections related to changes in the temperature and salinity with a lateral sampling of nearly 13 m. These reflections are corroborated by the processing of oceanographic parameters collected near to the seismic line, in a time gap of 30 days.

In terms of oceanographic analysis, a mixing layer of 50 m depth was detected in all five stations. The values of temperature and salinity are the expected for the three water masses present in the region: Tropical Water (TW), South Atlantic Central Water (SACW) and Antarctic Intermediate Water (AAIW). The combined seismic and oceanographic analysis also showed a large transition layer among the water masses, that difficult its detection via acoustic reflection.

The processing of the seismic line allows identifying reflection events in portions of the water column between the 350 m and 550 m depth, that can be separated in two portions: the central and bottom portions of the water column. The events in the central portion occur in the SACW and are related to the vertical mixing process within SACW and the lower part of the TW. The reflection close to the bottom portion was a result of the interaction between the water mass and the ocean bottom, which may contain turbulent mixing. Regarding reflections more distant of the coast, it is suggested that represents the boundary region between the SACW and AAIW.

The combined analysis of the seismic lines and the data from the oceanographic stations offered robustness to the results and made easier the interpretation about the reflections events. The peaks in the reflectivity curves generated by the oceanographic parameters followed the same trend present in the seismic reflections, validating both analyses.

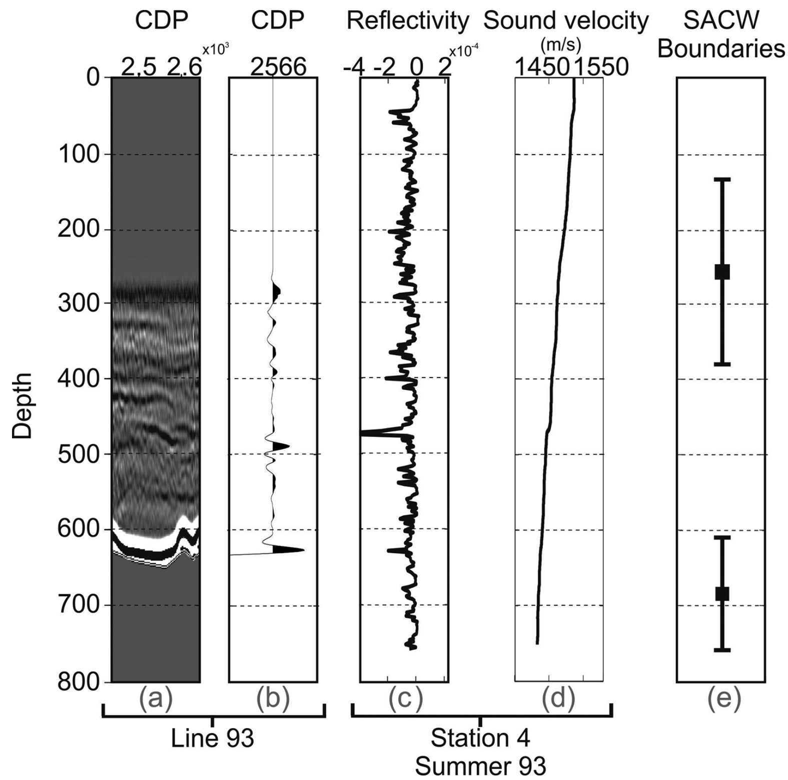

Figure 9 – Combination among seismic section at intervals of CDP 2430 to 2640 (a), CDP 2556 profile (b), result of seismic processing and reflectivity (c), sound velocity profiles (d) obtained from CTD stations and the SACW boundaries obtained in the literature (e).

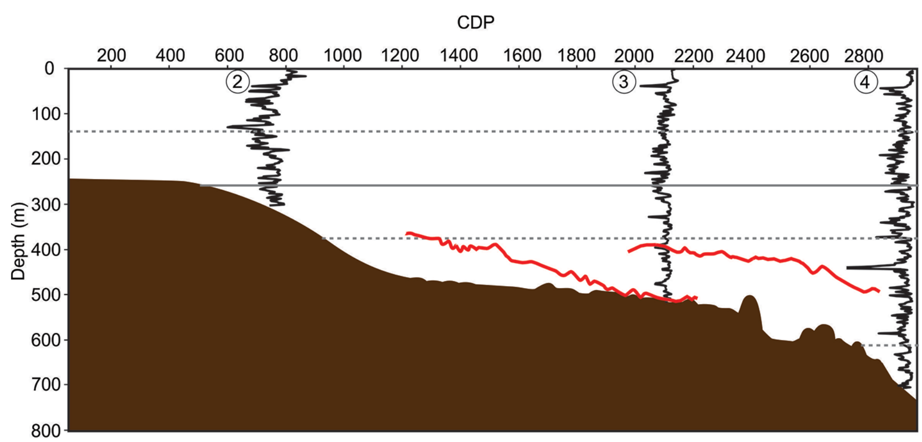

Figure 10 – The localization of the main reflections according the reflectivity profiles at the stations 2, 3 and 4.

The combined analysis also had shown that the evaluation of an acoustical parameter (reflectivity) can be used to find water masses. The Antarctic Intermediate Water was detected in station 5, located near to 720 m depth and represented by relative low reflectivity values.

Despite the limitation associated with the use of legacy data, industry seismic data proved to be an unprecedented source of relative inexpensive data that can be used to complement the oceanographic research and to understand mesoscales structures.

Researches in seismic oceanography show the possibility to identify submesoscale and finescale structures. However, more studies are needed to identify this possibility using available data in the petroleum industry.

ACKNOWLEDGEMENTS

The first author has been supported by program "Ciências do Mar" (43/2013), financed by CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) – Brazilian Federal Agency for Support and Evaluation of Graduate Education within the Ministry of Education of Brazil. The authors are deeply grateful to Ph.D. Dirk Klaeschen to provide the script to direct wave remotion and Ph.D. Berta Biescas for all support in the discussions and processing steps. The authors acknowledge the CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for funding this project via the following grants: CNPq – Bolsa de Produtividade em Pesquisa Nível 2 – CA OC – Oceanografia; processo 313777/2013-6, and INCT MarCOI "Oceanografia Integrada e Usos Múltiplos da Plataforma Continental e Oceano Adjacente – Centro de Oceanografia Integrada (COI)".

REFERENCES

BIESCAS B, SALLARÈS V, PELEGRÍ JL, MACHÍ F, CARBONELL R, BUFFETT G, DAÑOBEITIA JJ & CALAHORRANO A. 2008. Imaging meddy finestructure using multichannel seismic reflection data. Geophys. Res. Lett., 35(11): L11609.

BIESCAS B, RUDDICK BR, NEDIMOVIC MR, SALLARÈS V, BORNSTEIN G & MOJICA JF. 2014. Recovery of temperature, salinity, and potential density from ocean reflectivity. J. Geophys. Res. Oceans, 119(5): 3171–3184.

BLACIC T & HOLBROOK WS. 2009. First images and orientation of internal waves from a 3-D seismic oceanography data set. Ocean Sci., 6(3): 341–439.

BILÓ TC, DA SILVEIRA ICA, BELO WC, DE CASTRO BM & PIOLA AR. 2014. Methods for estimating the velocities of the Brazil Current in the pre-salt reservoir area off southeast Brazil (23°S-26°S). Ocean Dyn., 64(10): 1431–1446.

BOYER TP, ANTONOV JI, BARANOVA OK, COLEMAN C, GARCIA HE, GRODSKY A, JOHNSON DR, LOCARNINI RA, MISHONOV AV, O'BRIEN TD, PAVER CR, REAGAN JR, SEIDOV D, SMOLYAR IV & ZWENG MM. 2013. World Ocean Database 2013. In: LEVITUS S (Ed.). & MISHONOV A (Tech. Ed.). NOAA Atlas NESDIS 72. Silver Spring, MD, 209 pp.

BUFFETT G, BIESCAS B, PELEGRI J, MACHIN F, SALLAÈS V, CARBONELL R, KLAESCHEN D & HOBBS R. 2009. Seismic reflection along the path of the Mediterranean Undercurrent. Cont. Shelf Res., 29(15): 1848–1860.

CAMPOS EJ, GONÇALVES JE & IKEDA Y. 1995. Water mass characteristics and geostrophic circulation in the South Brazil Bight: Summer of 1991. J. Geophys. Res. Oceans, 100(C9): 18537–18550.

CARNIEL S, BERGAMASCO A, BOOK JW, HOBBS RW, SCLAVO M & WOOD WT. 2012. Tracking bottom waters in the Southern Adriatic Sea applying seismic oceanography techniques. Cont. Shelf Res., 44: 30–38.

DA SILVEIRA ICA, SCHMIDT ACK, CAMPOS EJD, GODOI SS & IKEDA Y. 2000. A corrente do Brasil ao largo da costa leste brasileira. Rev. Bras. Ocean, 48(2): 171–183.

FOFONOFF NP & MILLARD JR RC. 1983. Algorithms for computation of fundamental properties of seawater. UNESCO Technical Papers in Marine Science.

FORTIN WF & HOLBROOK WS. 2009. Sound speed requirements for optimal imaging of seismic oceanography data. Geophys. Res. Lett., 36(24): 4 pp.

FER I & HOLBROOK WS. 2008. Seismic reflection methods for study of the water column. Elements of Physical Oceanography: A Derivative of the Encyclopedia of Ocean Sciences, p. 432–441.

HOLBROOK WS & FER I. 2005. Ocean internal wave spectra inferred from seismic reflection transects. Geophys. Res. Lett., 32(15): L15604.

HOLBROOK WS, PÁRAMO P, PEARSE S & SCHMITT RW. 2003. Thermohaline fine structure in an oceanographic front from seismic reflection profiling. Science, 301(5634): 821–824.

IOC, SCOR & IAPSO. 2010. The international thermodynamic equation of seawater – 2010: Calculation and use of thermodynamic properties. Intergovernmental Oceanographic Commission, Manuals and Guides No.56, UNESCO, 196 pp.

LAMPITT RS, FAVALI P, BARNES CR, CHURCH MJ, CRONIN MF, HILL KL, KANEDA Y, KARL DM, KNAP AH, McPHADEN MJ, NITTIS KA, PRIEDE IG, ROLIN J-F, SEND U, TENG C-C, TRULL TW, WALLACE DWR & WELLER RA. 2010. In situ sustained Eulerian observatories. Proceedings of the Ocean Obs., v. 9, 27 pp.

LEGEAIS JF, OLLITRAULT M & ARHAN M. 2013. Lagrangian observations in the Intermediate Western Boundary Current of the South Atlantic. Deep-Sea Res., II(85): 109–126.

MOJICA JF. 2015. Estrategias del procesado y análisis espectral de datos sísmicos para el estudio de procesos dinámicos en oceanografía física. Tesis de Doctorat. Universitat de Barcelona. Facultat de Geologia. 318 pp.

MÜLLER TJ, IKEDA Y, ZANGENBERG N & NONATO LV. 1998. Direct measurements of the western boundary currents off Brazil between 20°S and 28°S. J. Geophys. Res., 103(C3): 5429–5437.

NANDI P, HOLBROOK WS, PEARSE S, PÁRAMO P & SCHMITT RW. 2004. Seismic reflection imaging of water mass boundaries in the Norwegian Sea. Geophys. Res. Lett., 31(23): L23311.

PAPENBERG C, KLAESCHEN D, KRAHMANN G & HOBBS RW. 2010. Ocean temperature and salinity inverted from combined hydrographic and seismic data. Geophys. Res. Lett., 37(4): L04601.

PIÉTÉ H, MARIÉ L, MARSSET B, THOMAS Y & GUTSCHER MA. 2013. Seismic reflection imaging of shallow oceanographic structures. J. Geophys. Res. Oceans., 118(5): 2329–2344.

PINHEIRO LM, SONG H, 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. J. Marine Syst., 79(1-2): 89–100.

RUDDICK B, SONG H, DONG C & PINHEIRO L. 2009. Water column seismic images as maps of temperature gradient. Oceanography, 22(1): 192–205.

SALLARÈS V, MOJICA JF, BIESCAS B, KLAESCHEN D & GRÀCIA E. 2016. Characterization of the submesoscale energy cascade in the Alboran Sea thermocline from spectral analysis of high resolution MCS data. Geophys. Res. Lett., 43(12): 6461–6468.

SHEEN KL, WHITE NJ & HOBBS RW. 2009. Estimating mixing rates from seismic images of oceanic structure. Geophys. Res. Lett., 36(24): L00D04.

SILVA LCC. 2006. Estudo das Massas D'água e da Circulação Geostrófica na região Sudeste da Bacia do Brasil. Master Dissertation, Universidade Federal do Rio de Janeiro, COPPE, Brazil. 127 pp.

STRAMMA L & ENGLAND M. 1999. On the water masses and mean circulation of the South Atlantic Ocean. J. Geophys. Res. Oceans., 104(C9): 20863–20883.

TANG Q, WANG C, WANG D & PAWLOWICZ R. 2014. Seismic, satellite, and site observations of internal solitary waves in the NE South China Sea. Sci. Rep., 4: 5374.

THOMSON RE & EMERY WJ. 2014. Data analysis methods in physical oceanography. Ed.Ñewnes. 716 pp.

YILMAZ Ö. 2001. Seismic data analysis: Processing, inversion, and interpretation of seismic data. Society of Exploration Geophysicists. 2227 pp.

Recebido em 4 abril, 2017 / Aceito em 19 fevereiro, 2018
Received on April 4, 2017 / Accepted on February 19, 2018