Offshore seismic reflection data: an oceanographic perspective

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ABSTRACT Recent studies have demonstrated that offshore seismic reflection data can be used to detect boundaries in the water column. This novel approach, called "seismic oceanography", has produced clear pictures of water mass interfaces (i.e., thermoclines, internal waves, fronts, eddies) in different oceanic environments. As the study of ocean circulation requires an extensive spatial and temporal coverage of observations, the possibility of using seismic data available from industrial or academic investigations to support and enhance oceanographic surveys seems very challenging. Since the Southern Ocean represents a key study area for climate due to the deep water formation process which triggers the Global Thermohaline Circulation, we began to reprocess seismic lines recently acquired off Wilkes Land (east Antarctica) in the framework of the WEGA project, to investigate the presence of reflections in the seawater column. A first evaluation of the possibility of recognizing fine structures in the water column is positive: seismic lines acquired along the Wilkes Land continental margin show signals correlated with boundaries inferred by conventional oceanographic measurements.

1. Introduction

The ocean circulation plays a key role on the control of global climate and understanding processes such as mixing, dense water formation and deep convection is fundamental to assess the ocean-atmosphere interactions, which ultimately regulate the climate. To investigate ocean circulation and its temporal variability a broad spatial and temporal coverage of observations is required and this challenges the development of new observational technologies and the synergy between different disciplines.

The study of ocean circulation is based on the identification and mapping of water masses with different physical and chemical properties (i.e., temperature, salinity, chemical tracers), which form at the surface and maintain their own distinctive features within the ocean. The conventional approach to investigate water mass characteristics is performed acquiring vertical profiles of temperature and salinity with a submersible probe (CTD: conductivity, temperature and depth profiler) lowered from a ship at discrete locations. To overcome the problem of synopticity and of limited horizontal resolution of CTD data, remotely sensed data (i.e., sea surface temperature, ocean colour and high resolution altimetric measurements of sea surface height) acquired by satellites are now routinely used, together with networks of temperature and salinity probes (e.g., expendable bathythermograph: XBT and expendable CTD: XCTD) launched by ships during navigation.

The integration of oceanographic data with information derived from multichannel seismic data has been recently proposed by Holbrook *et al*. (2003). In this landmark paper, authors demonstrate that offshore seismic data provide good quality images of oceanic thermohaline structures and offer a new tool to efficiently survey large ocean volumes at high horizontal resolution. The term "seismic oceanography" was coined to define this new multidisciplinary approach.

Based on the promising first results, seismic datasets previously acquired for lithospheric exploration have been reprocessed to focus on the seawater column reflectivity (i.e., Hardy *et al*., 2007) and new joint seismic and oceanographic surveys have been undertaken (i.e., Nandi *et al*., 2004; Tsuji *et al*., 2005; Nakamura *et al*., 2006).

Starting from 1988, OGS has collected about 37,000 km offshore reflection seismic data in Antarctica with R/V OGS Explora for lithospheric exploration, and has participated in several scientific international collaborations in the Southern Ocean.

As the ocean around Antarctica is a key study area for the global thermohaline circulation, we reprocessed seismic data acquired along the Wilkes Land margin (East Antarctica) to perform a first evaluation of the possibility of using multichannel seismic data to recognize hydrological boundaries in the water column.

2. Seismic oceanography

First approaches in the use of low frequency (10-100 Hz) reflection seismic to detect water stratifications were reported by Gonella and Michon (1988) and Phillips and Dean (1991). Yilmaz and Doherty (2001) reported an example of reflected signals within the water column to illustrate the concept of impedance contrast in reflection seismology. In conventional offshore seismic surveys, seawater velocity variations produced differential reflected signal delays that were computed to apply static correction for 3D data sets (Wombell, 1997). Also, for 4D time-lapse seismic surveys, the impact of velocity variations has to be taken into account to improve the data repeatability (Bertrand and Mac Beth, 2003; Vesnaver *et al*., 2003).

Holbrook *et al*. (2003) obtained seismic sections of the water column off Newfoundland, Canada, showing signals related to the major oceanographic front between the Labrador Current and the North Atlantic Current. In this pioneering study, data validation was performed by the comparison with hydrographic data acquired during separate oceanographic studies. In the conventional seismic surveys for lithospheric exploration, well stratigraphy is an important constraint to calibrate the data. In the seismic oceanography case, where a dynamic component is expected, synoptic hydrological measurements are an important piece of information to correctly interpret reflections in the water column. A first contemporaneous seismic and oceanographic survey was conducted by Nandi *et al*. (2004) in the Norwegian Sea. Simultaneous temperature (from XBT) and temperature and salinity (from XCTD) data along the seismic line were acquired to quantify the sensitivity of the seismic reflection method to small changes in seawater temperature. In that experiment, seismic data were acquired by a 6 km long streamer (480 channels) and 6 air guns with a total volume of 122 liters.

On the same seismic data set, Paramo and Holbrook (2005) undertook amplitude versus offset (AVO) analysis to quantify temperature contrasts. Tsuji *et al*. (2005) used 3D seismic volume to image fine structures related to the Kuroshio current south of Japan. Simultaneous seismic and hydrographic measurements (XCTD, XBT) were carried out in east Japan to map the mixing between the warm Kuroshio and the cold Oyashio Currents (Nakamura *et al*., 2006). During the survey different air gun configurations and shot intervals were tested and fine structures characterized by ~ 0.5°C temperature contrasts were successfully imaged with 3.4 litre GI airgun and 16-fold data. Hardy *et al*. (2007) reprocessed seismic profiles collected over the continental slope west of Ireland and obtained oceanic thermohaline structures in the Rockall Trough.

On the basis of the interesting results emerging from the cross-disciplinary approach, the EU funded the 'Geophysical Oceanography (GO)' project (2007-2009, http://www.dur.ac.uk/eu.go). Recently, in the frame of the International Polar Year, the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) financed EGLACOM project (Rebesco and EGLACOM working group, 2008), a joint seismic-oceanographic cruise to explore the lithosphere and hydrosphere (Petronio *et al*., 2009) along the Svalbard continental margin.

3. Water mass boundary reflections

The seismic reflection method relies on the detection of reflected signals originated from an incident wave at the interface between media with different seismic impedance. The reflection coefficient depends on the seismic impedance contrast and on the incidence angle (Zoeppritz, 1919). The magnitude of the reflection coefficient for ocean bottom signals ranges between 0.1 and 0.6 for soft and hard sea floor, respectively, while typical intra-column seawater values can reach 0.007 in presence of strong water temperature contrasts (e.g., 5°C). The seawater column reflections have a weak amplitude in respect to the sea bottom reflection, nevertheless, the joint seismic and oceanographic measurements demonstrate that seismic impedance contrasts due to a small temperature difference (e.g., 0.4 – 0.03°C) can be distinguished (Nandi *et al*., 2004).

The detection of signals produced by a weak impedance contrast depends on the instrumentation (i.e., seismic source, hydrophone sensitivity, resolution and internal noise of the seismic recording system) and on the coherent and random noise level.

As the reflections produced by water column stratification arrive after the direct water wave and before water-bottom reflection, no interference with the other seismic events produced by the actual shot is observed. Nevertheless, strong interferences can derive from late arrivals and multiple signals produced by previous shots. This coherent noise affects continuous seismic recording in deep water (Tucker and Yorston, 1973; McBride *et al*., 1994b), and the sea-land wide-angle seismic survey typically acquired in the frame of crustal exploration projects (Flueh and Dickmann, 1992). The wrap-around effect of the energy from previous shots can obscure the actual reflections in the common-shot-gather domain. As these interfering events have different NMO velocities, dynamic corrections computed with correct velocities and CDP stack can improve the signal to noise ratio. However, in presence of low fold coverage data, the weak primary seawater reflectivity can still be contaminated by multiple wrap-around energy.

A proper choice of the acquisition parameters can improve the quality of the seawater seismic section. Larger shooting intervals reduce the amplitude of the wrap-around energy. Not constant interval shooting time (Sachpazi *et al*., 1997) favors the misalignment of multiple signals in CDP domain with a consequent amplitude decrease in the stack.

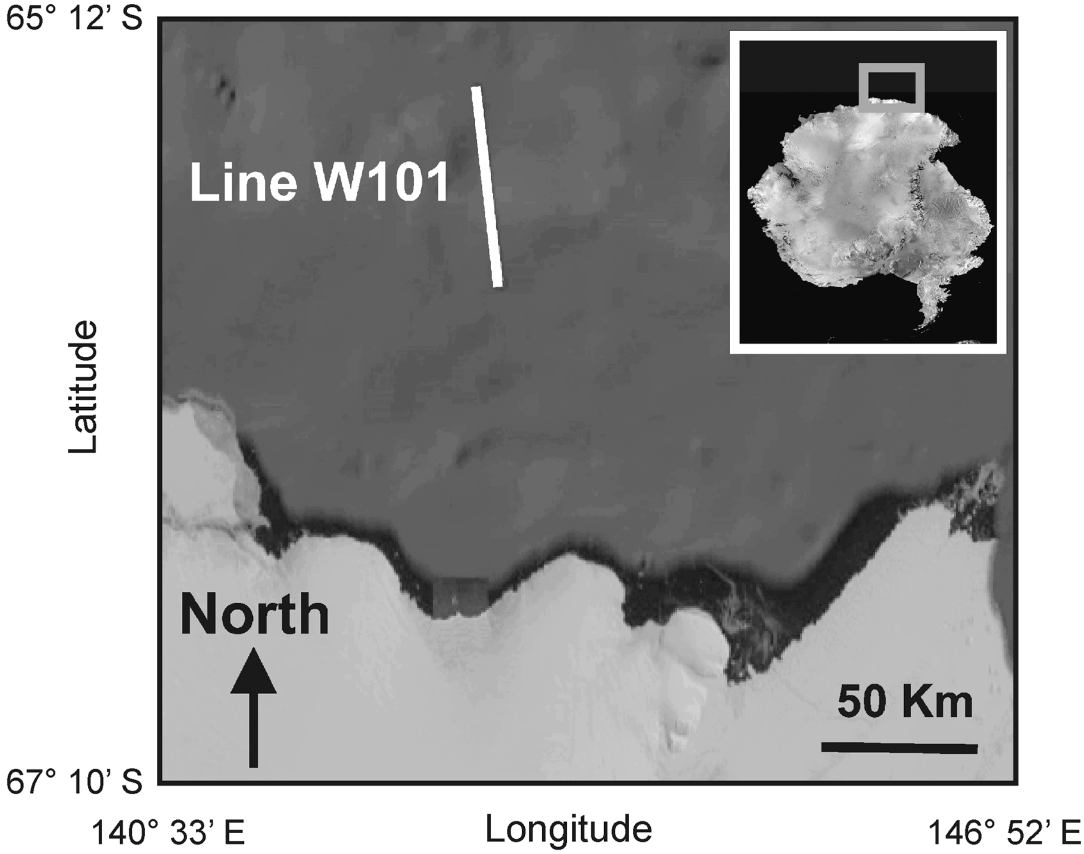

Fig. 1 - Survey area.

In presence of a hard ocean bottom and/or survey with short shooting time interval, the multiple energy of previous shots can completely obscure the signals. In this case, the application of only CDP sorting, NMO and stack can be insufficient to "stack-out" the coherent noise. The application of the prestack multiple removal techniques is required (Hardy and Hobbs, 1991) to avoid misinterpretation of the primary reflected wavefield (McBride *et al*., 1994a).

The interval shooting time/distance, hydrophone streamer length, gun type and total volume depend on the target depth/required resolution. Shooting intervals of 25 - 75 m with multichannel (48 – 480) streamer 0.6 – 6 km length allow a multifold coverage ranging from 12 - 240%.

The minimum depth of investigation is affected by the minimum available offset. Typical values (e.g., 100 – 300 m) do not allow the illumination of the shallower portion of the seawater column where boundaries can be present (e.g., seasonal thermocline).

4. Data analysis and processing

We reprocessed the high-resolution seismic line W101 collected in the frame of WEGA project, an international, multidisciplinary project, funded by the Italian Progetto Nazionale

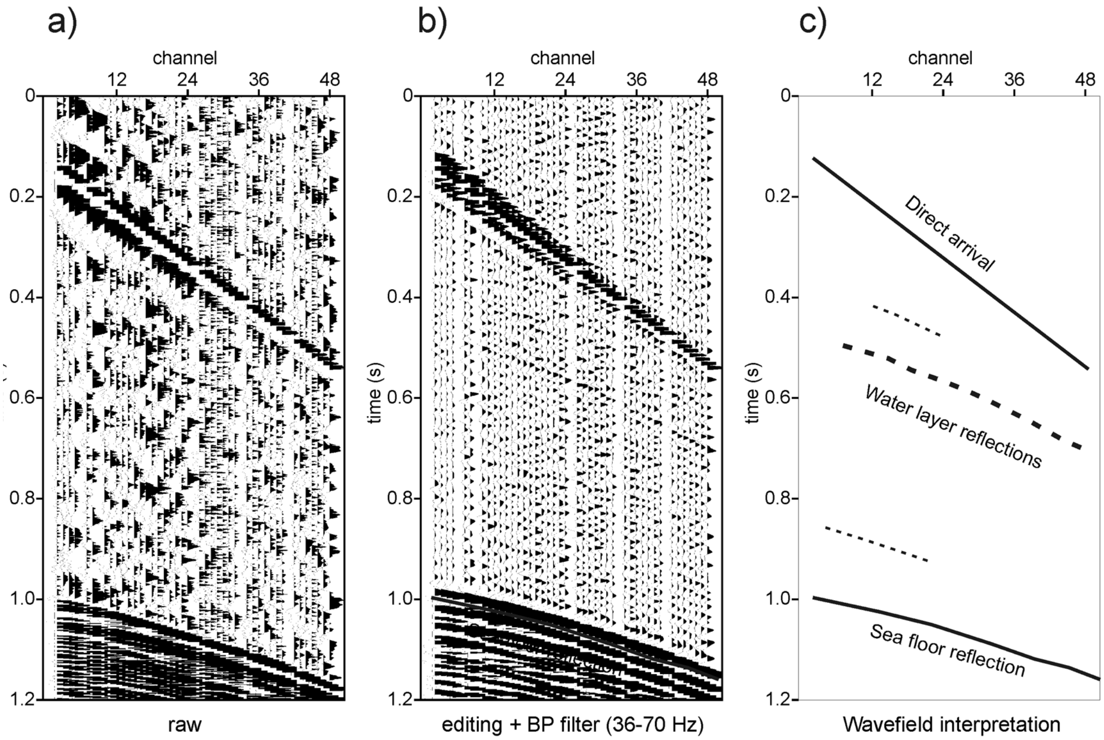

Fig. 2 - Prestack data example: (a) raw data, (b) after editing and bandpass filtering (36-70 Hz) and (c) wavefield interpretation. Dashed lines indicate the weak seawater reflections.

Ricerche in Antartide and the Australian Antarctic Division. Fig. 1 shows the position of the acquisition area. The high-resolution seismic line W101 was collected off Wilkes Land (East Antarctica) by R/V Tangaroa during the austral summer 2000 (Brancolini and Harris, 2000; De Santis *et al*., 2003). The multichannel seismic data were acquired with 48-channel, 600 m-long streamer, minimum offset 170 m. Shots generated by 2 GI airguns (6.8 litres, 2000 psi) were fired at a constant time interval of 5 s (~ 25 m) resulting in nominally 12-fold data.

Reduced volume airgun source and low fold coverage differentiate this line from the data sets successfully processed by others authors (e.g., Holbrook *et al*., 2003; Nandi *et al*., 2004; Hardy *et al*., 2007; etc.). The initial data inspection showed the presence of remarkable coherent and random noise so, considering the weak amplitude of the seawater interfaces and the low fold coverage, we performed a preliminary shot by shot analysis in order to be confident with the presence of a real primary reflected signal and to avoid mistakes in the interpretation of a stacked section (Tucker and Yorston, 1973). As the data result from the superposition of the primary events, background noise, and arrivals from previous shots, we computed synthetic seismograms to support the interpretation in the common shot gather domain. Fig. 2 shows a common-shot-gather with wavefield interpretation.

The brute stack showed some seawater column reflections but noise was preponderant. Data quality control with the consequent noisy trace removal was performed. Several common-shot-

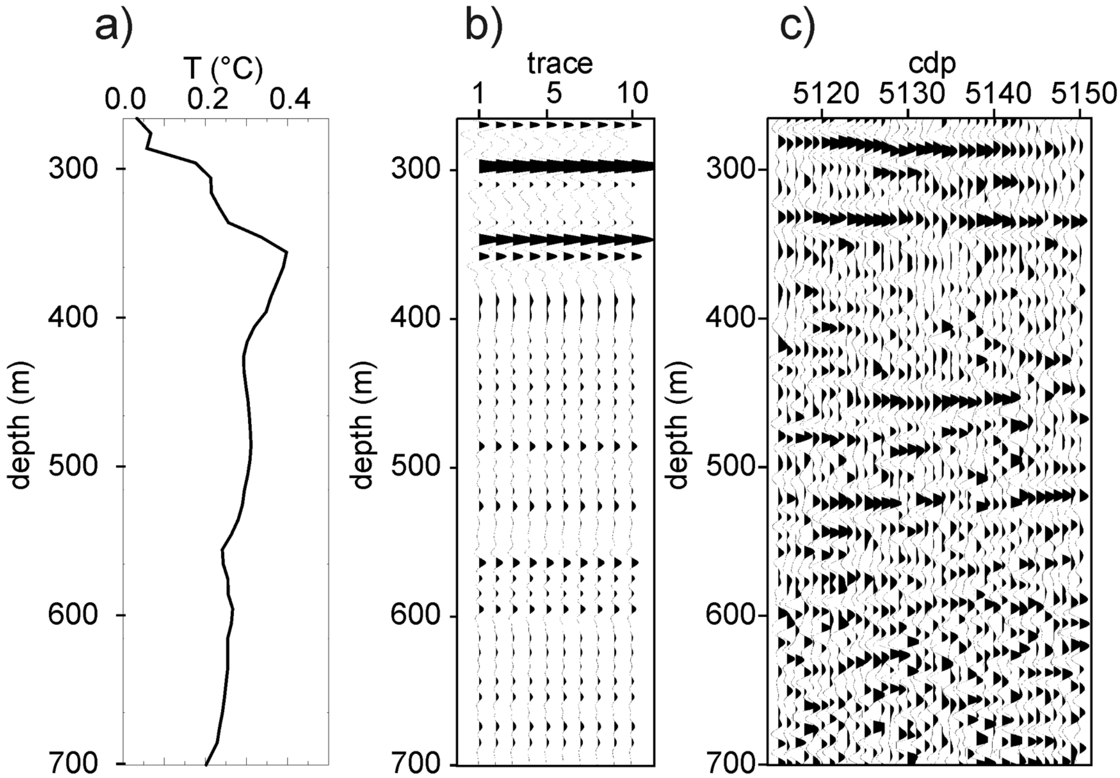

Fig. 3 - Oceanographic- and seismic- data correlation: a) temperature profile, b) synthetic trace computed from CTD data (10 equal traces are used for display purposes), and c) real stacked data.

gathers were characterized by strong background noise, and, in some cases we observed duplication of first arrivals probably due to an airgun malfunction (i.e., autofire).

The reduced multifold coverage of this line (12), and the presence of relevant background noise required a processing sequence modified in respect to that proposed by other authors for long streamer data (e.g., Holbrook *et al.*, 2003; Hardy *et al.*, 2007; etc.). The processing steps adopted for the seismic line are: geometry definition, trace editing, bandpass filtering, spherical divergence compensation, median filter, CDP sorting, NMO correction and stack. We applied a median filter in subtraction mode to enhance the weak reflections as for the wavefield separation in VSP data processing (Hardage, 2000).

5. Results

Reflection amplitude generated in correspondence with the interface between water strata with different physical properties are very small with respect to the other reflections (i.e., primaries and multiples). In the prestack processing stage, we use synthetic data to support the interpretation of the water column reflections in the common shot gather domain. As no contemporary in situ hydrographic profiles were carried out during the seismic survey, we used

CTD data acquired in the same area to validate the CDP stacked section. We computed a normal-incidence impedence reflectivity as a function of depth with velocity and density values obtained from CTD data measured at about 2 km westwards of the CDP n. 5115. We used MacKenzie's (1981) empirical formula, and Fofonoff and Millard (1983) to obtain P velocity and density, respectively. Fig. 3 presents the comparison between the temperature profile, the synthetic traces obtained from CTD data and real seismic data. The temperature profile shows a complex vertical structure characterised by two major gradients in the upper 400 m, and some minor variations below indicating the presence of water masses with different thermohaline properties. Data above a 275 m depth are not shown because the NMO stretch mute is applied. The reflectivity pattern in synthetic and real data are similar: strong signals in correspondence of two major temperature contrasts ($\Delta T = 0.2°C$) at 300 and 350 m, respectively, can be detected. These temperature variations correspond to reflection coefficients of about 0.0002 – 0.0003.

The temperature maximum in the vertical CTD profile at 350 m corresponds to the Circumpolar Deep Water (Rintoul, 2007), which is the deeper portion of the Antarctic Circumpolar Current (ACC), a prominent ocean current that flows around Antarctica. The discrepancies in water depth between real- and synthetic-seismic data is ascribable to the different periods of acquisition of these two data sets, as hydrodynamic structures within the ACC are characterized by significant spatial and temporal variability (Tomczak and Liefrink, 2005). Below 400 m depth other minor signals can be observed indicating the presence of fine structures within the water mass, with different thermohaline properties.

Fig. 4a shows the CDP stacked data along the Wilkes Land continental slope. The seismic signals validated by CTD data can be laterally extrapolated with a higher spatial resolution compared with conventional oceanographic measurements. A line drawing of the principal reflections is depicted in Fig. 4b. In the northernmost part of the seismic section, two strong near horizontal signals at about 290 and 330 m depth can be recognized. At increasing depth (about 450, 530, and 600 m) dipping boundaries can be observed. Approaching the continental shelf these boundaries rise, forming a complex reflectivity pattern with shallower signals.

6. Conclusions

As documented in recent years by several authors, conventional offshore seismic reflection data can be used to image boundaries in the seawater column.

While for high fold coverage data a simple conventional processing sequence can be successfully applied, in case of low fold data, standard elaboration is not sufficient to obtain reliable results. In particular, surveys performed on the continental shelf with a strong wrap-around noise represent a processing challenge.

We reprocessed a high resolution, low multifold coverage seismic line acquired along the Wilkes Land continental margin. Along the continental slope, a complex reflection pattern in the seawater column was detected. In this survey, we are able to investigate oceanic fine structures with a resolution limit of about 8 m, assuming the Rayleigh criterion (1/4 wavelength). Based on the CTD measurements, we computed synthetic traces to help the interpretation of the seismic data. We tentatively correlate the seismic signals with oceanographic boundaries recognized in hydrological data. Taking into account the non-coincident measurements and the variability of the

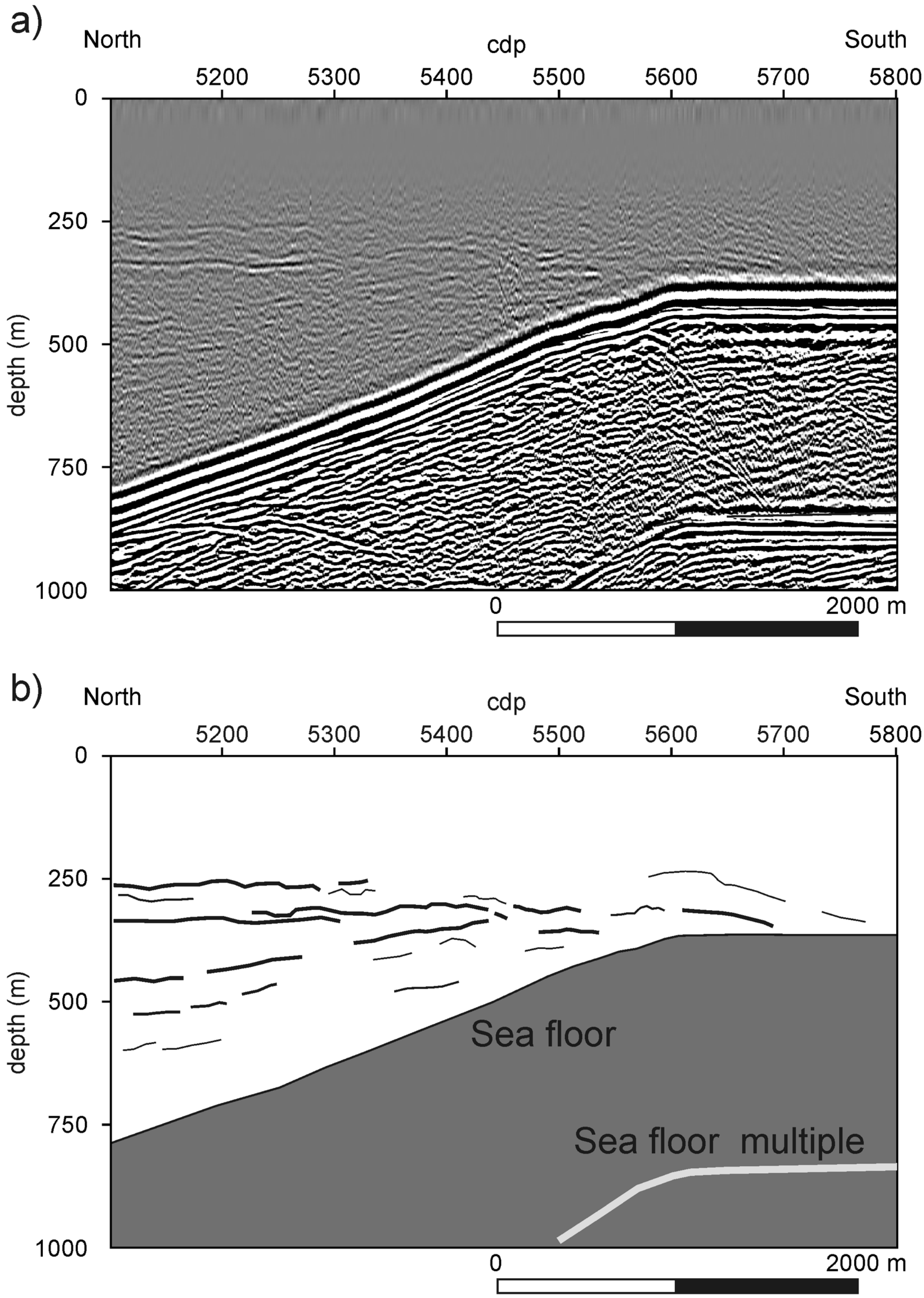

Fig. 4 - Portion of the seismic line W101 converted to depth (a) and line drawing (b). The strong northern dipping signal corresponds to the sea bottom. The seafloor multiple is also evident. Along the Wilkes Lands continental slope, a complex reflection pattern in the seawater column is observable.

observed oceanographic phenomena, the real and synthetic data show good agreement.

The aim of this work is to evaluate the capability of the offshore seismic reflection to illuminate boundaries in the Antarctic water masses. As seawater column signals are very weak, the strong effort in the use of this approach is to define a processing flow able to obtain reliable signals. More speculative oceanographic results can be obtained after processing a larger spatial coverage of seismic lines where oceanographic data for validation are available, which, unfortunately was not our case. As in conventional seismic surveys, the presence of a well permits data calibration, also seismic oceanography needs coincident and simultaneous oceanographic measurements (e.g., CTD, XBT) for "ground truth". Recent projects have been designed according to these requirements (Nandi *et al*., 2004; Nakamura *et al*., 2006; Hobbs, 2008; Petronio *et al*., 2009).

Large offshore seismic data sets acquired worldwide offer a new perspective for a reprocessing oriented to obtain "historical pictures" of the oceans. This approach could be useful for climate change studies with a low cost impact. In the case of lack of coincident conventional oceanographic data, only persistent phenomena with slow variability (e.g., major ocean currents) can be mapped, using data available from the World Ocean Database for correct interpretation of seismic signals. Considering that the first offshore seismic surveys were carried out in the 1970's, a potential 40-year window of interesting information is still contained in several worldwide archives.

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