GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L00D09, doi:10.1029/2009GL040820, 2009

High resolution seismic imaging of the ocean structure using a small volume airgun source array in the Gulf of Cadiz

L. Geli,[1] E. Cosquer,[1] R. W. Hobbs,[2] D. Klaeschen,[3] C. Papenberg,[3] Y. Thomas,[1] C. Menesguen,[1] and B. L. Hua[1]

Received 9 September 2009; revised 29 October 2009; accepted 2 November 2009; published 3 December 2009.

[1] A small volume (117 cu-inch) seismic source producing signal predominantly in the 150–200 Hz frequency window was used during the GO calibration experiment in the Gulf of Cadiz (April–May 2007). The data show the small scale (<10 m in the z direction) internal structure of the ocean. High-resolution images display seismic reflectors that often appear as distinct, horizontal, short (~a few hundred meters to a few km long) segments, lying at different depths, while low-resolution (~20 to 30 Hz) display long, horizontal reflectors (~a few tens of km), sometimes linked by short, apparently "dipping" segments. The present data suggest that this apparent dipping effect is due to the insufficient separation power (~λ/4) of the low resolution data. Improving high resolution acquisition systems hence appears to be a critical challenge to understand the seismic response of the ocean. **Citation:** Geli, L., E. Cosquer, R. W. Hobbs, D. Klaeschen, C. Papenberg, Y. Thomas, C. Menesguen, and B. L. Hua (2009), High resolution seismic imaging of the ocean structure using a small volume airgun source array in the Gulf of Cadiz, *Geophys. Res. Lett.*, *36*, L00D09, doi:10.1029/2009GL040820.

1. Introduction

[2] Recent research [*Holbrook et al.*, 2003; *Holbrook and Fer*, 2005; *Nandi et al.*, 2004] has shown that the boundaries which separate water masses with different physical properties (temperature, salinity) can be successfully imaged with standard multichannel seismic (MCS) techniques. Such techniques have been commonly used for long in marine geosciences and in the oil industry to investigate the geological structure of the substratum. The energy produced by a seismic source near the sea surface is reflected at the boundaries between the water layers. For vertical incidences, the reflection coefficient (R) is equal to the impedance contrast across the boundary:

$$R(z) = \frac{d(\rho v)}{\rho(z)v(z)} \quad (1)$$

where ρ(z) and v(z) are density and velocity at depth z, respectively. The impedance contrast R characterizes the reflectivity of the boundary. Previous studies [e.g., *Nandi et al.*, 2005] have shown that impedance contrasts produced by temperature variations of a few hundredths of °C can be detected using seismic methods with a lateral resolution that is generally less than 10 m, well beyond what is usually obtained in standard oceanographic experiments.

[3] The vertical resolution, however, is limited by the frequency content of the seismic signal [*Hobbs et al.*, 2009] while strong reflectors near the top and bottom of Meddies [e.g., *Bower et al.*, 1997], are not produced by single interfaces but by boundary zones made of finely-scaled layers, a few meters thick (see Figure 1 and Appendix 1 in Text S1 of the auxiliary material).[4] Imaging small scale (~a few m) structures is a critical issue for addressing fundamental questions in physical oceanography that requires high resolution seismics, particularly to determine whether energy transfer from large to small scales is a self-similar process.

2. Acquisition System

[4] During the EC-Funded GO experiment different seismic sources were used to seismically image the internal structure of the Mediterranean Water Outflow at different scales in the Gulf of Cadiz [e.g., *Hobbs*, 2007; *Hobbs et al.*, 2009]. In this paper, we present the results that were obtained with an airgun array source having a maximum usable frequency of over 250 Hz, giving at vertical resolution of less than 6 m ($\lambda/4 \approx 1.5$ m). In total 500 km of High-Resolution (HR) seismic profiles were collected (Figure 2) together with vertical logs of the water physical properties from about 160 XBTs or XCTDs.

[5] The seismic acquisition system was based on 6 SODERA® mini GI-Guns with two air chambers: the Generator (G) for producing the primary air bubble; and the Injector (I) released after a given time delay, for limiting the primary bubble oscillation. Two sub-arrays of 3 airguns (with volumes of 24/24 and 15/15 cu-inch, respectively) spaced apart by 10 m, were towed at 1.5 meters below sea surface fired in harmonic mode, with a total generator air volume of 117 cubic inches ~2 liters (in comparison, the Low-Resolution (LR) source deployed during the second part of the GO experiment used a total volume of air of 2320 cu-inches ~38 liters).

[6] The seismic data was recorded on a 450-m long streamer with 72 channels (group spacing of 6.25 m) and optimal towing depth at 2 m (frequency notch at 400 Hz). The weather encountered during the cruise allows most profiles to be recorded at the optimal depth. Shots were fired

[1]Ifremer, Plouzané, France.
[2]Department of Earth Sciences, University of Durham, Durham, UK.
[3]Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Kiel, Germany.

0094-8276/09/2009GL040820$05.00

[4]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040820.

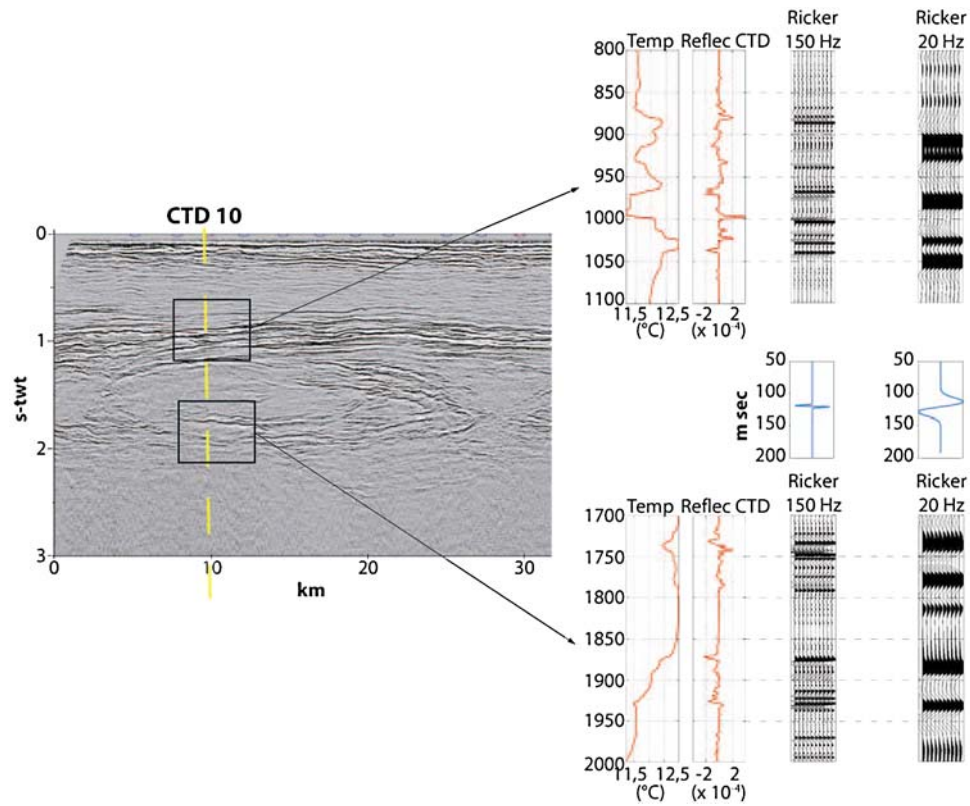

Figure 1. Seismic image of a meddy along profile LR01 obtained with RRS Discovery during the second leg of the GO experiment (may 2007) using a standard, low-resolution source of 2320 cu-inches producing signal with predominant frequencies in the 20–30 Hz window. This section overlaps with Line HR-018 shown in Figure 2, but was shot two weeks later. The yellow line indicates the location of CTD 10, collected with F/S Poseidon as seismic data was acquired. Reflectivity may be directly computed based on the CTD data, using formula (1). Theoretically, the derivative expressed in formula (1) is valid when dz tends to zero. In practice, however, dz depends on the sampling rate available along a vertical column. In the present case, the CTD data has been resampled at 1m in order to avoid short wavelength noise, so dz = 1 m. The right part of the figure represent Seawater Temperature, Reflectivity and synthetic seismogram in response to Ricker wavelets at dominant frequency of 20 Hz and 150 Hz in, respectively, the [0.8–1.1] and [1.7–2.0] seconds two-way travel-time (s-twt) windows. Figure 1 clearly shows that the strong reflectors at the top and at the bottom of the meddy are not related to sharp interfaces. Instead, they are related to transition zones made of small-scale layers, less than ~ 5 to 10 meters thick. See also Appendix 1 of Text S1.

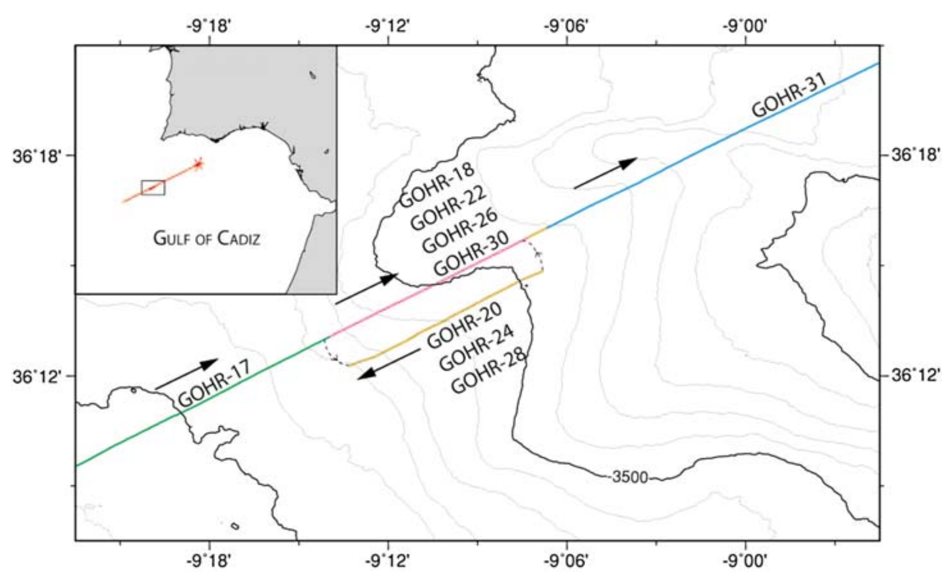

Figure 2. Implementation of the HR seismic lines collected during the GO experiment in April/May 2007 in the Gulf of Cadiz.

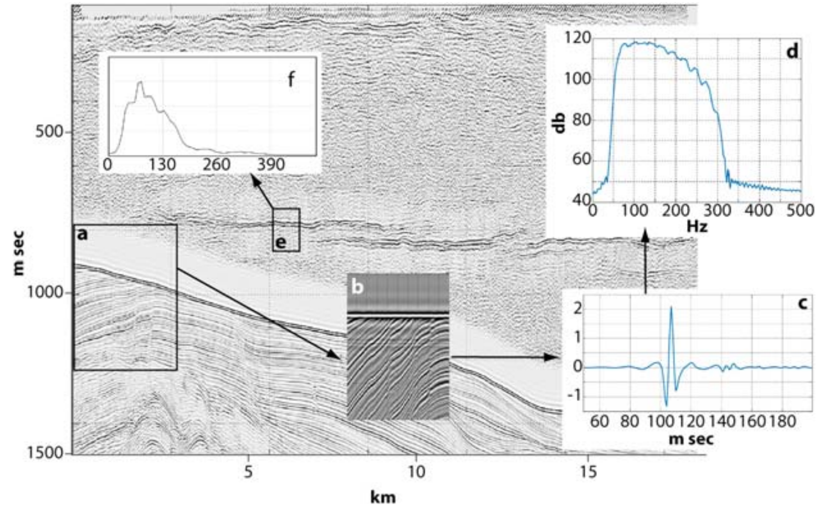

Figure 3. Migrated High resolution seismic line HR-10 obtained with the small volume source of 117 cu-inch described in the text. Automatic Gain Control is applied, producing an artificial blank above seabottom. The wavelet extracted from the sea-bottom reflection exhibits a spectrum with predominant frequencies in the [150–200] Hz window (insets a to d). In contrast, the wavelet extracted from the reflector in the water column (insets e and f) is characterized by lower frequencies, predominantly in the [50–130 Hz] window, suggesting that the small-scale internal structure of the ocean produces a low-pass filter effect.

every 10 s (~25 m with a ship's speed ~5 knots). Though in theory the optimum Common-Depth Point (CDP) spacing is 3.125 m, the CDPs have been stacked by pairs giving a spacing of 6.25m to enhance signal to noise ratio.

3. Data Processing

[7] Seismic processing was specifically designed for the water column, after having muted the data from below the seafloor. The processing workflow includes: Butterworth filtering; spatial binning; removal of the direct arrival; NMO with water velocity 1510 m/s; stack and migration. An example of migrated HR seismic section is shown in Figure 3. The HR acquisition system allows imaging from about 40 m to depths of about 1500 m. A consistent correlation is observed between seismic reflectors and vertical temperature gradients based on XBTs/XCTDs.

[8] An advanced shot-gather procedure was developed at IFM-GEOMAR, in order to improve the efficiency of the processing by keeping the characteristic amplitude spectra of the unwanted events. The following sequence was constructed: a minimum delay filter 2/5 Hz was applied to remove non seismic events (noise), while keeping full amplitude spectra of the direct wave, back scattered tail boy waves, and reflected waves; then, the direct wave was extracted by Karhunen-Loeve filter, followed by amplitude matching and substraction; to remove the remaining noise created from this procedure, a high-pass zero phase filter (20/40 Hz) was applied; then, two tau-p filters were applied to remove steeply dipping events (tail boy noise, ship noise, ...) having a broader frequency range than the main reflected events; additional high amplitude, low-frequency events were detected in time slice mode, and filtered using a final high-pass frequency filter (30/50 Hz); eventually, true amplitude common offset migration was applied with sound speed information from simultaneous oceanographic measurements (XBTs).

[9] Post-processing (migration, spike-deconvolution) of the HR data did not quite enhance the resolution as wished. The 3-D nature of water-column reflectors seems to be more sensitive to HR data than, i.e., experienced with low resolution data. The impact of moving reflector boundaries on seismic processing methods [*Klaeschen et al.*, 2009] is not yet fully understood, but clearly complicates the migration and deconvolution, especially for HR data. In conclusion, the shot generated noise and the limited amount of energy produced by the small source volume results in a low signal-to-noise ratio, that demands careful pre- and post-processing to recover the weak signals. However, although low in quality (compared to LR data), only HR data provides the temporal resolution to study the effect of "seismic oceanography" at small scales.

4. Filtering Effect of the Water Column

[10] The bandwith (50–250 Hz) of the reflection on the seabottom is centered around 150 Hz. In contrast, the bandwith of the internal reflection within the water column is centered around 100 Hz (Figure 3). This effect maybe explained by the short-wavelength (<5 m) internal structure of the water column, which tends to filter out the higher frequencies of the seismic signal (see Appendix 2 of Text S1). Unlike the solid Earth, the water does not support sharp discontinuities because diffusive effects of both heat and mass create smooth boundary zones leading to the observed loss of the higher frequency energy.

5. Short and Flat Versus Longer and "Dipping" Reflectors

[11] High-resolution (~150 Hz) images display seismic reflectors that often appear as distinct, horizontal, short (~a few km long) segments, lying at different depths below sea-level, while low-resolution (~20 to 30 Hz) often display

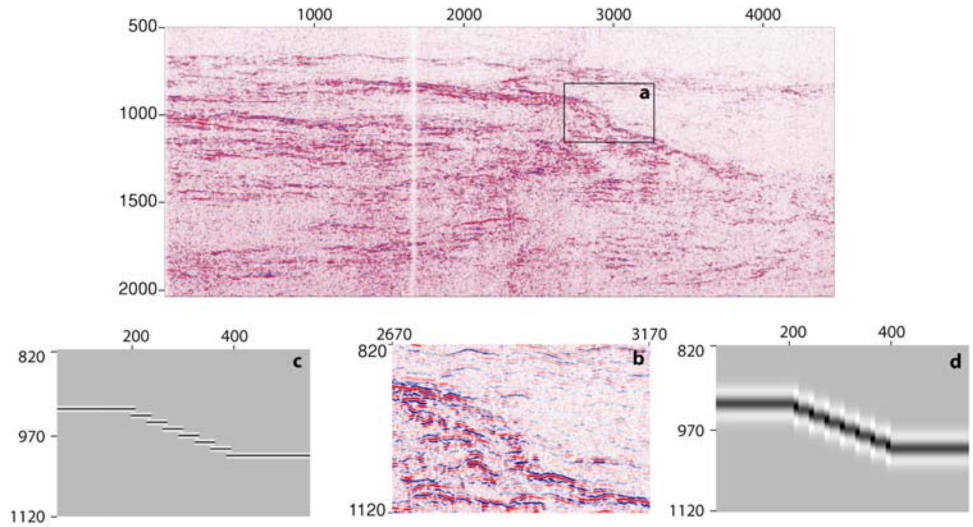

Figure 4. HR image (lines 30–31) of a meddy, showing signal down to 1.5–2 s-twt. Main boundaries are made of a series of short, flat reflectors, that may appear as "dipping reflectors" when imaged with low resolution seismics. Insets c and d show the seismic response of a staircase structure to Ricker wavelets at 150 and 20 Hz respectively (vertical stair spacing is here equal to 7.5 m). It is important to highlight that the "dipping" effect is not totally an artifact, as infinite horizontal layers would not produce dipping reflectors. The reflectors appear as "dipping" because the boundary consist in a staircase made of sharp interfaces of limited horizontal extent.

long horizontal reflectors (~a few tens of km) linked by short, apparently "dipping" segments. Such reflectors have sometimes been misinterpreted as "dipping" boundaries separating different water masses apparently crossing isopycnals, but actually result from the insufficient resolving power of the low-resolution seismic data. As illustrated in Figure 4, an interface made of spatially distinct, flat segments lying at different depths may appear either as a series of flat reflectors at high-resolution, but as one single, apparently dipping, boundary at low-resolution. This is particularly important when describing the boundaries of Meddies, which are actually made of a stack of flat reflectors, a few hundreds of meters to a few kilometers long. This result confirms previous observations (G. Krahmann, personal communication, 2009) based on repeated "yoyo" CTD hydrocasts made with R/V POSEIDON during time periods of 12 hours, which showed that seismic reflectors are systematically close to isopycnals.

6. Short Scale Temporal Variability

[12] Thanks to maneuverability of the High-Resolution acquisition system, 7 sections (10 km-long each) were shot repeatedly every two hours on the continental slope (near 36°13′N, 9°10′W), showing the short-scale temporal variation of the reflectivity of the water column (Figure 5). This variability, which could depend on tidal effects, confirms the results obtained with the "yoyo" hydrocasts, which showed an apparent vertical oscillation of the isopycnals.

7. Discussion

[13] The small volume (117 cu-inch) mini GI-gun seismic source used during the GO calibration experiment provided high resolution seismic data, which, despite the low signal to noise ratio, shed new insight on the internal structure of the ocean. Improving the S/N ratio of high resolution seismics appears to be a challenge of critical importance, not only to image the small scale (~a few m in depth) structures, but also to help understand the seismic images that we presently have from the ocean.

[14] To reach this challenge, one cannot play on the fold coverage by increasing the length of the streamer, due to the filtering effect of the receiver at large incidence angles. At frequencies >175 Hz, the antenna effect is such that the amplitude of the seismic signal is divided by a factor of two at incidence angles greater than ~60°: so the amplitude of the reflections from the shallower-most interfaces decreases rapidly as the source-receiver offset increases.

[15] The solution consists in increasing the seismic energy emitted in the water column. Seismic airguns produce their acoustic radiation by the release of high pressure air into the water. The acoustic energy output is a complex relationship between the physical shape of the gun, the air-pressure, the chamber volume, the ambient temperature and hydrostatic pressure [*Parkes and Hatton*, 1986]. The bubble period T and amplitude A of the pulse emitted by one a single gun of volume V increases as $V^{1/3}$ when the pressure and depth are held constant: the higher the frequency of the pulse, the smaller the volume of the source and the smaller the amplitude of the seismic signal. So the optimum design to improve the signal to noise ratio require arrays with a very large number of small volume guns, as this is a more effective means to increase output energy over simply increasing the volume. The high-frequency characteristics can be further improved by the use of GI or mini GI-guns as used here as these suppress the bubble pulse giving an improved impulsive source. However though high-frequency energy help resolve the fine structure, the loss of the low frequency energy means information on the larger vertical scale struc-

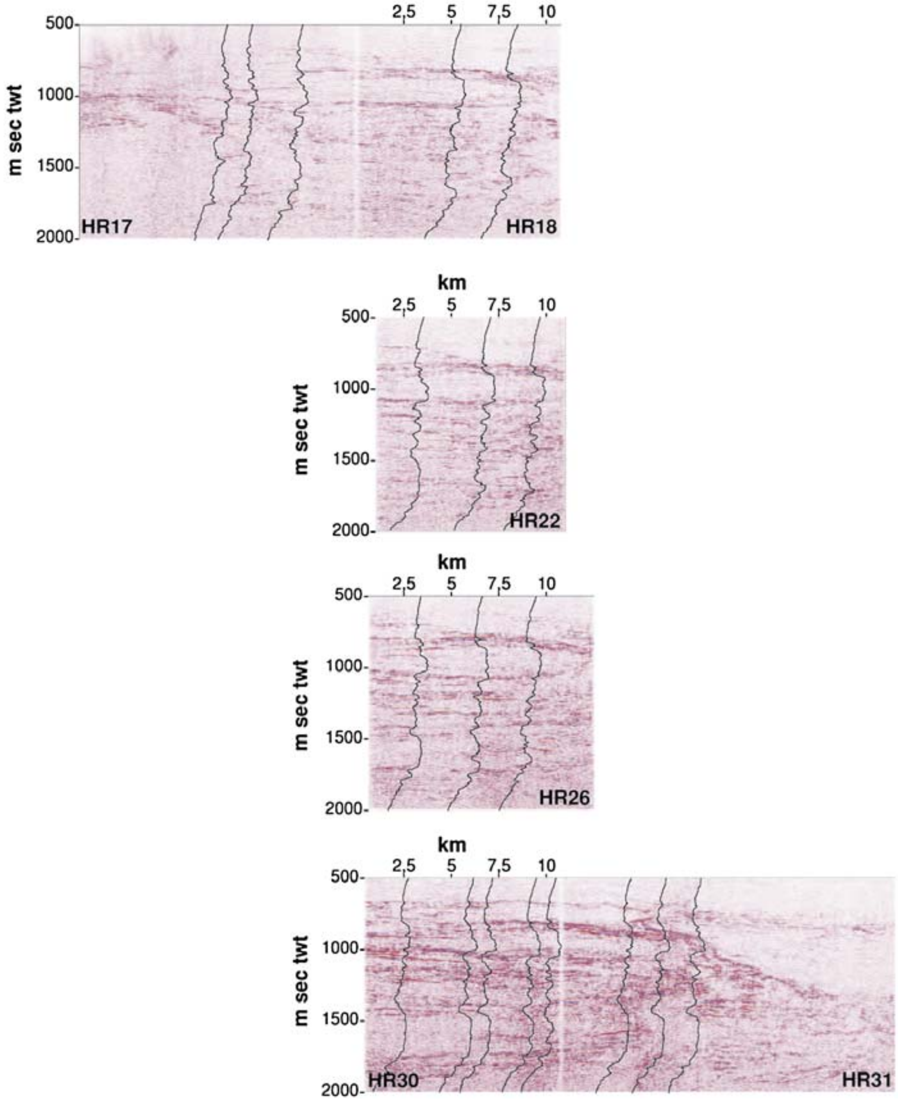

Figure 5. High-resolution seismic sections, shot repeatedly every four hours from the SW to the NE, on the continental slope (near 36°13′N, 9°10′W), showing the short-scale temporal variation of the water column.

tures is missing. This challenge can be addressed by using a broad-band system as proposed by *Hobbs et al.* [2009], with sources and receivers towed at different depths.

8. Conclusions

[16] By using high-frequency a seismic source we have been able to image the fine-scale water structure down to a vertical resolution compatible with CTD casts and a horizontal resolution of 6.25 m. This has revealed new insights into the spatial nature of boundaries in the water layer. In particular the evidence that boundaries tend to form along isopycnals. If the interface between two water masses is inclined then the reflectors form a shingled staircase of short sub-horizontal events. Previous seismic imaging of these boundaries using low-resolution systems had produced evidence of "dipping" events. From a simple model and from direct observation of the boundaries of a Meddy in the Gulf of Cadiz, we conclude that these effects result from the seismic acquisition system.

[17] **Acknowledgments.** The GO project was funded by the 6th Framework Programme for Research and Development of the European Community (grant FP6-NEST-15603). The captain and crew of RRS Discovery are greatly acknowledged. The authors of the present paper wish to thank all other partners that made the GO project a success, particularly Gerd Krahmann, who made possible the use of F/S Poseidon with support of the German Science Foundation. Help from Frauke Klingelhoefer, Bruno Marsset, Elise Quentel, Ekaterina Vsemirnova, Laetitia Morvan, Estelle Thérêau is also acknowledged. Careful reviews helped improve the manuscript.

References

Bower, A. S., L. Armi, and I. Ambar (1997), Lagrangian observations of Meddy formation during a Mediterranean undercurrent seeding experiment, *J. Phys. Oceanogr.*, *27*, 2545–2575, doi:10.1175/1520-0485(1997)027<2545:LOOMFD>2.0.CO;2.

Hobbs, R. W. (2007), PROJECT: GO—Geophysical Oceanography—A new tool to understand the thermal structure and dynamics of oceans, *Eur. Union Newsl.*, *2*, 7.

Hobbs, R. W., D. Klaeschen, V. Sallarès, E. Vsemirnova, and C. Papenberg (2009), Effect of seismic source bandwidth on reflection sections to image water structure, *Geophys. Res. Lett.*, *36*, L00D08, doi:10.1029/2009GL040215.

Holbrook, W. S., and I. Fer (2005), Ocean internal wave spectra inferred from seismic reflection transects, *Geophys. Res. Lett.*, *32*, L15604, doi:10.1029/2005GL023733.

Holbrook, W. S., P. Paramo, S. Pearse, and R. W. Schmitt (2003), Thermohaline fine structure in an oceanographic front from seismic reflection profiling, *Science*, *301*, 821–824, doi:10.1126/science.1085116.
Klaeschen, D., R. W. Hobbs, G. Krahmann, 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.
Nandi, P., W. S. Holbrook, S. Pearse, P. Páramo, and R. W. Schmitt (2004), Seismic reflection imaging of water mass boundaries in the Norwegian Sea, *Geophys. Res. Lett.*, *31*, L23311, doi:10.1029/2004GL021325.
Parkes, G., and L. Hatton (1986), *The Marine Seismic Source*, 184 pp., Kluwer Acad., Dordrecht, Netherlands.

E. Cosquer, L. Geli, B. L. Hua, C. Menesguen, and Y. Thomas, Ifremer, BP 70, F-29280 Plouzané, France. (geli@ifremer.fr)
R. W. Hobbs, Department of Earth Sciences, University of Durham, South Rd., Durham DH1 3LE, UK.
D. Klaeschen and C. Papenberg, Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Wischhofstr. 1-3, D-24148 Kiel, Germany.