

## SCIENTIFIC REPORT

# ESF Exploratory Workshop on Seismic Oceanography

Begur, Girona (Spain), 18-21 November 2008

Convened by:

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# 1<sup>st</sup> ESF EXPLORATORY WORKSHOP ON SEISMIC OCEANOGRAPHY

Parador d'Aiguablava, Begur, Spain  
November 19-21, 2008

## *Executive summary*

One of the most challenging tasks that is nowadays posed to Physical Oceanographers is the understanding of water mixing processes occurring in the ocean. These processes have small spatial scales in nature and conventional measurement techniques fail to provide sufficient information to improve knowledge and confirm/disprove theoretical findings.

The Multi-Channel Seismic method, used since many years in the field of Seismology, was recently confirmed to be an excellent tool to study small-scale oceanic processes. The method allows mapping, at extremely high lateral resolution, ocean acoustic reflectivity derived from acoustic impedance contrasts of layering associated to thermohaline fine-structure. Seismic Oceanography is thus emerging as a challenging interdisciplinary field that bridges the gap between Physical Oceanography and Seismology.

The 1<sup>st</sup> European Science Foundation Exploratory Workshop on Seismic Oceanography joined for the first time the major players in the discipline. A total of 34 scientists from 6 European countries (France, Germany, Ireland, Portugal, Spain, United Kingdom), United States of America, Canada, China and Japan joined efforts to take stock of the main achievements gathered so far and define strategies of common effort into the future.

The Workshop program was designed to cover oceanographic topics relevant to Seismic Oceanography and to discuss processing and seismic/oceanographic modelling techniques. The methodology was to have a series of presentations followed by thorough discussions, which proved to be invaluable. The first objective of the meeting was to proceed with a comprehensive identification of processes that potentially could be studied with the new tool. The different blocks were opened by keynote talks given by outstanding oceanographers to make oceanographic processes understandable by the seismological community. Several topics were addressed, like thermohaline fine-structure induced by double diffusive processes (salt fingering and diffusive layering) or lateral intrusions, internal waves, mesoscale geostrophic eddy stirring and turbulent dissipation. The participants focused on past and recent observational and theoretical results and identified open questions to which seismic measurements could potentially give a priceless contribution.

The second effort was to review and discuss seismic processing techniques aiming at identifying uncertainties of the method and establish which of the identified processes are actually being mapped in the acoustic observations. A few keynote talks were given by outstanding seismologists to make the principle, potential and limits of the seismic method transparent to the oceanographic community. The third objective, and one of the most important, was to foster cooperation among researchers with the clear intention of joining efforts, working towards the design of future experiments. It was clear from the discussion that process-oriented studies should be prioritized. In this context, a few processes/areas were suggested: turbulent bottom boundary layer mixing and

internal wave breaking over continental slopes and seamounts, mixing processes over the Mid-Atlantic Ridge, marginal sea overflows and interaction between the Gulf Stream current system and its associated eddies.

A promising future is envisaged to Seismic Oceanography from its capability to improve the understanding of the ocean as part of the Earth Climate System, and more particularly to help in better understanding ocean mixing processes.

## *Scientific content of the event*

Seismic oceanography is a recently launched discipline aiming at imaging the internal structure of oceans and at quantifying physical processes occurring within the water column using active seismic data. This new methodology provides images of the water column with an unprecedented lateral resolution. This images open new aspects and frontiers in research in physical oceanography. The ESF Exploratory Workshop on Seismic Oceanography aimed at sharing recent international achievements on the subject, identifying the research lines having the greatest potential and gathering future efforts to consolidate the discipline world wide.

The workshop was structured in three sessions, each one devoted to a specific aspect of technical and scientific questions related to the potential and of seismic oceanography. The three parts were the following ones: 1) Introduction, description of the methodology, successes and future challenges, 2) The current knowledge about physical processes in oceanography, and 3) The basis of imaging and inversion of seismic data. The first part was aimed at introducing the methodology and part of its specifics to the Physical Oceanography community. The second part was aimed to clarify the specifics of the processes that the physical oceanographers are interested in to the seismological community. The third part was devoted to describe the achievements of the seismic studies of images of oceanic processes and the attempts to quantify this physical processes.

Each of the sessions opened with a key note speaker that introduced the topic, followed by a series of talks that provided current research examples that posed unresolved questions to the participants. This generated thorough discussion thus a relatively large amount of time was devoted to the discussion at the end of each session. This was in addition to the discussion held at the end of each presentation.

The successes, challenges and new direction were introduced by S. Holbrook by showing images of different processes within the water column, features like: internal waves and their interaction with the sea bottom, the inter-relationship of the reflections, isotherms, isopycnals. Some challenges include: the quantification of turbulence phenomena by estimation of the horizontal spectra, as well as the determination of the physical properties of the water column from seismic data.

B. Ruddick provided an overview of the processes which could generate seismic reflection and why addressing specific studies that included published and unpublished material. This was complemented by specific contributions by R. Ferrari on the generation of Temperature-Salinity filaments by eddy stirring. This presentation included the comparison of seismic images and oceanographic data. A particular view of the structure and evolution of meddies was provided by L. Armi, which poses the statement that probably the most important value of this new methodology was its power to generate high resolution images. This unprecedented lateral resolution is the key to the understanding of the mixing processes in scenarios like the seabed, and/or the surroundings of sea mounts. Numerical models of meddies and the generation and evolution of their geometry and internal structure were presented by L. Hua in a talk entitled "Simulations of stratified turbulence surrounding the Meddy structure". Further, a quantitative study on the properties and propagation of internal waves were presented by L. St. Laurent and A. Viúdez presented the characteristics of inertia-gravity waves by balanced mesoscale eddies by. How internal waves could be measured using seismic data was the topic addressed by S. Jones, and an example of the research carried out on turbulence and internal wave spectra was presented by H. Song.

The seismic view on what does a seismic reflection image of the water most like represents were given by R. Hobbs. He provided images and experience from the European FP6 funded GO project. He also described specific details on the processing artifacts and new aspects of data acquisition such as the oceanic VSP. Furthermore, he emphasized the importance of the ocean as a moving mass of turbulent water this suggested the need for new developments and/or approaches to seismic data acquisition of imaging the water column. This was further discussed in a presentation by E. Vsemirnova. An analysis of the potential limits of the seismic methods in imaging the oceans finestructure was presented by V. Sallarès, and the relative contribution of the temperature and the salinity to the reflectivity sequence of the water column was discussed by B. Biescas.

D. Klaeschen presented new developments and challenges for acoustic wave propagation and inversion of physical parameters. He showed technical details for the quantification of the physical properties of the ocean finestructure using seismic data and that of the relative motion of moving water masses. The data was mostly a direct and outstanding result derived from the GO data set. This session also included new numerical developments on seismic wave propagation modelling in a media which features extremely low reflection coefficients (on the order of  $10e-4$  which are characteristic of the layering within the thermaline layer. This was introduced by J. Kormann. The most outstanding results concerning the inversion of physical properties of the finestructure layering from seismic data and at the highest seismic resolution were presented and discussed in detail in two talks one by C. Papenberg, and a second one by T. Tsuji.

R. Schmitt introduced the quantification of several physical processes in oceanography and how they could be assessed by this new discipline. The potential of seismic oceanography to quantify the horizontal spectra of turbulence and internal waves was presented by J. M. Klymak, and L. Gostiaux presented a case study on deep internal waves and vertical thermal structure affected by the passage of an eddy. A new view on the characterization of turbulence phenomena was put forward by G. Buffett introducing stochastic heterogeneity mapping. Numerical simulations of the generation and evolution of meddies were presented by N. Serra. The models clearly illustrated the transient nature of the seismic images and the effort that should be made in order to quantify motion on seismic images. The introduction of other measuring methodologies of the physical parameters to help constrain the physical properties of the media were discussed. Yoyo-CTD measurements at the Meddy's edge were presented by G. Karhmann. Discussion on different results provided by the GO project, such as the fine-structure related to the Mediterranean outflow water were presented by E. Quentel and J. Huthnance. The latter presented a comparison with seismic images.

The final oral presentations included one by L. Pinheiro on a very detailed image of a seismic profile offshore Portugal illustrating the variety of structures which can be identified in a marine water seismic section and this was a clear example that there is still a very long way to go to understand all the dynamics that are taking place in the mixing process. Large and small meddies, highly reflective dipping structures, possible filaments, all were present in this seismic section. Furthermore, this presentation was an illustration of the value of legacy data L. Géli discussed the possibilities of small volume sources to provide high resolution images of the water structure.

The coffee breaks took place at the poster area where the posters were up for discussion during the whole workshop. The authors of the poster gave a 5 minutes presentation in order to bring up the most outstanding aspects of their work. 14 posters that addressed the major topics of the workshop were presented with a very high interest rate.

## *Assessment of the results, contribution to the future direction of the field, outcome*

The last session of the workshop was an open discussion of the results presented during the previous two days, their impact and future opportunities for collaborative interdisciplinary research between seismologists and oceanographers chaired by Steve Holbrook (U. Wyoming, USA) and Richard Hobbs (U. Durham, UK).

From a physical oceanography viewpoint the key results are:

- the unprecedented horizontal spatial sampling. Seismic oceanography offers typically 3 orders of magnitude better lateral sampling of the ocean compared with standard CTD profiles
- position of water masses in the ocean. For the first time oceanographers can visualise the relationships between ocean features and their detailed measurements
- the ability to map perturbation on boundaries that can be analysed using spectral methods and compared with estimates of internal wave spectra (Garrett-Munk) and identify areas that are inconsistent with that expected
- the potential of the method to address fundamental processes, especially that of mixing; either by internal waves or turbulence.

The EU commission funded GO-project was recognised as a major success. The integration of classical physical oceanography measurements with seismic imaging was proof that the results from the combination of the methods was far greater than would have been achieved by each method on its own. This alone was an important result and focused thoughts on the need for future integrated experiments. In addition new analysis methods being developed by GO participants will yield new information for understanding ocean processes and will need to be exploited on both legacy data and included in future projects.

There was general agreement in that process-oriented studies were the most interesting for the future development of seismic oceanography. A vigorous discussion was held about what were the key processes that could most benefit from combined seismic and physical oceanography data:

- horizontal coherence of boundaries
- structure induced by strain
- 'staircases' created by double diffusion processes
- improved estimates of dissipation/diffusion rates
- organisation of internal waves, are they in groups
- effects of topography
- boundary effects e.g. when internal waves interact with the continental slope
- turbulent flow and vortices and relationship of internal waves with eddies

However, it was recognised that there were some targets that would be unsuitable for the method such as deep water where the impedance contrasts are too small to create a reflected seismic wavefield.

It was agreed that broadband seismic data offered the most opportunities with a source frequency range from less than 10 Hz to over 200 Hz as these data could then be used to resolve features in the ocean on a range of length scales from temperature/salinity gradients of 100 m down to discrete boundaries which maybe less than a few metres thick. This would require a high energy source tuned to give a broad frequency response. Ideally the seabed should have a sedimentary cover the help damp out unwanted reverberation in the water layer that would effectively increase noise and reduce the ability to capture the weakest reflections typically caused by temperature changes of +/- 0.01°C. However, for shallow targets, less than 1 km depth, a small compact seismic system like that used on part of the GO cruise would offer opportunities to undertake combined seismic and physical oceanography without the requirement of a dedicated vessel specially adapted for seismic work.

There was a majority in favour of producing a special publication from the results presented at the workshop. It was agreed that ten or more short papers would be submitted to Geophysical Research Letters for a special publication that would capture the key results presented and would bring the potential of the method to the widest audience. A web-based bulletin-board will be set up for the workshop participants so they can continue the discussions in a forum and a documentary of the meeting (video of talks and presentation slides with interviews) will be made available, initially for participants but once papers are in-press then to the public through the Seismic Oceanography Workshop web-site.

Further, a bid will be made the European Science Foundation for a Research Networking Programme as the community realised that this cross disciplinary discussion must continue. Such a network would allow exchange of personnel and know-how and help funding future workshops. There is the possibility to bid for funds in the US for international interdisciplinary collaborative research (\$1-2M) that would be sufficient for a future US led project on a similar scale to the EU GO-project. In addition, EU partners would try to get seismic oceanography adopted by the ESF EUROCORES programme and look to FP7 as a means to fund future projects.

In any such bid legacy physical oceanography and seismic data would be the key to possible success as would be used to provide evidence of the methods and highlight the synergy from a combined programme.

There was also discussion that maybe the equipment available today may not give the best configurations for mapping the water layer and some thought would need to be given for the development of new equipment that could would give better spatial coverage at possibly less cost.

## ***Final Scientific Programme***

**WEDNESDAY, NOVEMBER 19th**

- 8:00 WELCOME to the ESF Exploratory Workshop on Seismic Oceanography  
*Juan José Dañobeitia (CSIC Representative, UTM Director)*
- 8:10 PRESENTATION of the ESF and Standing Committee  
*Isabel Ambar (ESF Rapporteur)*
- 8:20 **S0.1. KEYNOTE TALK:** Five years of Seismic Oceanography: Successes, Challenges, and Future Directions.  
*W. Steven Holbrook (University of Wyoming, Laramie, USA)*

### **S1. PHYSICAL PROCESSES IN OCEANOGRAPHY (I)**

**Chair:** *Nuno Serra (University of Hamburg, Hamburg, Germany)*

- 9:00 **S1.1. KEYNOTE TALK:** Ocean processes that create seismic reflectors  
*Barry Ruddick (Dalhousie University, Halifax, Canada)*
- 9:40 **S1.2.** T-S filaments generated by eddy stirring and seismic imagery  
*R. Ferrari*
- 10:00 **S1.3.** Meddies: structure and evolution  
*L. Armi*
- 10:20-10:50 **Posters & Coffee Break**
- 10:50 **S1.4.** Simulations of stratified turbulence surrounding Meddy structures  
*L. Hua*
- 11:10 **S1.5.** Hydrodynamic, thermodynamic, and acoustic properties of large-amplitude internal waves  
*L. St. Laurent*
- 11:30 **S1.6.** Spontaneous generation of Inertia-gravity waves by balanced flow in the ocean  
*A. Viúdez*
- 11:50–13:10 **Open Discussion**

### **S2. IMAGING AND INVERSION OF SEISMIC DATA (I)**

**Chair:** *Ramon Carbonell (Institute of Earth Sciences “Jaume Almera”, Barcelona, Spain)*

- 14:30 **S2.1. KEYNOTE TALK:** What does a seismic section represent?  
*Richard Hobbs (University of Durham, Durham, UK)*
- 15:10 **S2.2.** Potential and limits of seismic methods to image oceans finestructure  
*V. Sallarès, B. Biescas, R. Carbonell, G. Buffett, J.L. Pelegrí*
- 15:30 **S2.3.** Simulation of a seismic dataset over a model of a dynamic ocean  
*E. Vsemirnova, R. Hoobs and N. Serra*
- 16:50-16:20 **Posters & Coffee Break**
- 16:20 **S2.4. KEYNOTE TALK:** Acoustic wave propagation and inversion of physical parameters  
*Dirk Klaeschen (Ifm-Geomar, Kiel, Germany)*



- 17:00 **S2.5.** Second-order CFS-PML algorithm for modelling seismic oceanography experiments.  
*J. Kormann, B. Biescas, P. Cobo, V. Sallarès, R. Carbonell*
- 17:20 **S2.6.** Seismic processing and inversion methods in seismic oceanography – latest results.  
*C. Papenberg and D. Klaeschen*
- 17:40 **S4.4.** Thermohaline finestructure distribution across the Kuroshio current.  
*T. Tsuji, S. Minato, T. Matsuoka, T. Noguchi, Y. Nakamura and Y. Fukao*
- 18:00-20:00 **Open Discussion**

## THURSDAY, NOVEMBER 20th

### S3. PHYSICAL PROCESSES IN OCEANOGRAPHY (II)

**Chair:** *Barry Ruddick (Dalhousie University, Halifax, Canada)*

- 8:00 **S3.1. KEYNOTE TALK:** Quantifying physical processes with seismic oceanography  
*Raymond W. Schmitt (Woods Hole Oceanographic Inst., Woods Hole, US)*
- 8:40 **S3.2.** Understanding horizontal internal wave and turbulence spectra  
*J. M. Klymak and J. N. Moum*
- 9:00 **S3.3.** An attempt to quantify water flow dynamics from seismic reflection data  
*G. Buffett, R. Carbonell, B. Biescas, V. Sallarès*
- 9:20 **S3.4.** Deep internal waves and vertical thermal structure affected by the passage of a Meddy in the open Canary Basin  
*L. Gostiaux, and H. van Haren*
- 9:40 **S3.5.** The generation of Mediterranean water eddies: in situ observations and numerical simulations  
*N. Serra and I. Ambar*
- 10:00-10:30 **Posters & Coffee Break**
- 10:30 **S3.6.** Analysis of the Yoyo-CTD at the Meddy's Edge  
*G. Krahnemann, M. Vogt and P. Brandt*
- 10:50 **S3.7.** Mesoscale to fine-scale structures related to the Mediterranean outflow water: a correlation of joint seismic reflection and physical oceanographic data acquired during the GO cruise.  
*E. Quentel, L. Aranda, M-A. Gutscher, X. carton, R. Hobbs, L. Géli, E. Cosquer and L. Hua.*
- 11:10 **S3.8.** Gulf of Cadiz oceanography for comparison with seismic imaging.  
*J. Huthnance, I. Ambar, R. Alvarado, R. Hoobs, G. Krahnemann, P. Silva and E. Quentel*
- 11:30-13:10 **Open Discussion**

### S4. IMAGING AND INVERSION OF SEISMIC OCEANOGRAPHY DATA (II)

**Chair:** *Valentí Sallarès (Marine Technology Unit, CSIC, Barcelona, Spain)*

- 14:30 **S4.1.** Relative contribution of temperature and salinity to water column's acoustic reflectivity  
*B. Biescas, V. Sallarès, G. Buffet, R. Carbonell*
- 14:50 **S4.2.** Methods of measuring oceanic internal waves using seismic reflection data.  
*S. Jones*
- 15:10 **S4.3.** Researches on internal waves spectra of northeastern South China Sea from one reflection seismic profile.  
*H. Song, C. Dong, B. Ruddick and L. Pinheiro*
- 15:30 **S4.4.** Detailed 2-D imaging of the Mediterranean Outflow and Meddies off W Iberia from Multichannel Seismic Data.  
*L. Pinheiro, H. Song, B. Ruddick, J. Dubert, I. Ambar, K. Mustafa*
- 15:50 **S4.5.** High resolution seismic images of the water structure obtained with a small volume source array  
*L. Géli, R. Hobbs, D. Klaeschen, E. Cosquer, B. Marsset, F. Klingelhoeffer F., C. Pappenberg*
- 16:10 Oral presentation of posters (5' each)

**FRIDAY, NOVEMBER 21th**

**FINAL DISCUSSION AND DRAFT OF CONCLUSIONS**

**Chair:** *Richard Hobbs (University of Durham, Durham, UK)*

*W. Steven Holbrook (University of Wyoming, Laramie, USA)*

- 8:00-10:30 **Open Discussion**
- 10:30-11:00 **Posters & Coffee Break**
- 11:00-13:15 **Plans for follow-up research activities and/or collaborative actions**
- 13:15 **Goodbye**

## **POSTERS**

**P1.** Acoustic and chirp (3.5 kHz) gas detection within the submerged section of the North Anatolian Fault zone in the Sea of Marmara

*L. Géli, P. Henry, T. Zitter, S. Dupré and the MarNaut Science Party.*

**P2.** Seismic Processing and Inversion Methods in Seismic Oceanography? Latest results

*C. Papenberg, D. Klaeschen*

**P3.** To pick or not to pick: Accuracy and utility of sound speed models in processing seismic oceanography data

*W. Fortin, W.S. Holbrook, and R. Schmitt*

**P4.** Quantifying Turbulence Dissipation from Seismic Reflection Images

*W.S. Holbrook, R. W. Schmitt, I. Fer, W. Fortin, and **Error! Reference source not found.***

**P5.** Obtaining Seismic Images from Oceanographic Profiles using Morphing Techniques

*L. Matias, I. Ambar, and P. Silva*

**P6.** Exploring the fine-scale vertical variability of sound speed

*F. Machín, J.L. Pelegrí, B. Biescas and V. Sallares*

**P7.** Testing recovery of ocean properties using an emulation of internal wave surfaces

*E. Vsemirnova, R. Hobbs and A. Bargagli*

**P8.** First images from a 3D time-lapse seismic oceanography data set

*T. M. Blacic, W. S. Holbrook and J. C. Seymour*

**P9.** Seismic reflections within the water column south of South Africa: indications for the Agulhas Retroflexion

*G. Uenzelmann-Neben, D. Kläschen, G. Krahnemann, T. Reston, M. Visbeck*

**P10.** Thermohaline staircases viewed by contemporaneous seismic imaging

*I. Ambar, R. Bezerra, L. Pinheiro, P. Silva, N. Salvao*

**P11.** Seismic oceanography in Japan

*Y. Nakamura, T. Noguchi, T. Tsuji*

**P12.** Seismic Imaging Of The Southern Ocean

*K. Sheen, N. White and R. Hobbs*

**P13.** New Perspectives on the Physical Characterization of the Mediterranean Undercurrent

*G. Buffett, B. Biescas, F. Machin, V. Sallàres, J. Pelegrí, R. Carbonell, D. Klaschen, R. Hobbs*

**P14.** Velocity model inversion from seismic reflection stacked data using the Very Fast Simulated Annealing algorithm

*B. Biescas, A. Ribodetti, V. Sallàres, R. Carbonell, C. Papenberg, D. Klaschen*

## ***Final list of participants***

### ***Isabel Ambar (ESF Rapporteur)***

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## ***Statistical information***

(including ESF rapporteur)

### **Countries of Origin**

Portugal	3
US	5
Spain	7
France	4
UK	5
Ireland	1
Germany	5
Canada	2
Japan	2
Total	34

### **Gender:**

Female	8
Male	22
Total	30