9.3 Multiscale waveform tomography of the planet Earth

A. Context and state of the art

The development of high-performance computing and the design of new seismic acquisition technologies in earthquake seismology (for example, the US array) and controlled-source exploration open the door to the development of high-resolution tomographic methods such as full waveform inversion (FWI) for imaging the Earth at different scales. FWI (Virieux et Operto, 2009, pour une synthèse récente) is referred to as a nonlinear optimization problem which minimizes a distance between recorded and modeled seismic waveforms collected by dense acquisition devices to estimate parameters that represent the physical properties of the subsurface. The forward problem consists in the numerical resolution of the acousto/elasto-dynamic wave equation with volumetric methods such as finite-differences or spectral finite-element methods (e.g., Komatitsch et al., 2002). Due to the huge size of the data and model spaces (up to tens of Tbytes of data and tens to hundreds of millions of parameters), the inverse problem is solved with local optimization approaches where the gradient of the misfit function is efficiently computed with the adjoint-state method, a quite efficient technique for wave-equation problem. Ideally, using the phase and amplitudes of all of the seismic arrivals should lead to subsurface models with the highest resolution (down to half the minimum wavelength) and the most complete representation of subsurface physical properties governing propagation of seismic waves (P and S wave speeds, density, attenuation and anisotropy). However, depending of the application context, some compromises related to the amount of information involved in the inversion (selected arrivals, selected seismic attributes such as phase or travel times, simplified wave physics) are often used to deal with either the nonlinearity of the inverse problem, the uneven illumination of the subsurface and the reliability of some observables. One example of such simplified form of FWI widely used in earthquake seismology is finite-frequency traveltime tomography where only travel times (or phase) of selected wave packets are exploited while accounting for finite-frequency effects of seismic wave propagation.

After the earlier developments of its theoretical concepts in the eighties by Pr. A. Tarantola (IPGP), FWI has caused a reawakening interest in both exploration geophysics (in particular for oil prospection but also for near surface applications using both seismic and electromagnetic data and deep crustal investigation with OBS data) and earthquake seismology at lithospheric, continental and global scales. Therefore, this seismic imaging technology is currently contributing to cross-fertilize the know-how of a broad community of geophysicists and starts finding some applications on other scientific fields such as medical imaging and helioseismology. Geoazur has been at the forefront of the FWI technology since the early 2000s in the framework of the petroleum SEISCOPE consortium (https://seiscope.oca.eu/,https://seiscope2.osug.fr/). Moreover, application to earthquake data at the global scale is currently developed by E. Bozdag at Geoazur. In this proposal, we review different sub-projects related to FWI that will be carried out at Geoazur in the next years. These sub-projects concern both controlled-source (active) seismology and earthquake seismology at different scales and address both the imaging of the subsurface structures and the imaging of the source (co-seismic slip during earthquakes).

B Current activity

B.1 Sedimentary basin imaging by frequency-domain FWI: the FFWI code

We develop at Geoazur the *FFWI* frequency-domain FWI code (authors: A. Miniussi and S. Operto) which is more specifically dedicated to marine stationary-receiver surveys such as ocean bottom cable (OBC) or ocean bottom node/seismometer (OBN/S) acquisitions. Currently, this code is more specifically developed for high-resolution imaging of sedimentary basins in oil exploration.

This code relies on the direct multifrontal solver MUMPS (http://mumps.enseeiht.fr/) that is used to solve the sparse linear system resulting from the discretization of the time-harmonic wave equation. We applied the *FFWI* code to an industrial dataset collected in the North Sea in the 3.5Hz-10Hz frequency band (Fig. 1). This was to our knowledge the first application of direct solver-based FWI to a real 3D data case study (Operto et al., 2015). We have shown that our *frequency*-domain implementation can be applied with moderate computational resources to tackle industrial applications involving thousands of seismic sources and receivers. In particular, we have shown that our approach is faster by one order of magnitude compared to the most-widespread *time*-domain FWI codes for stationary-receiver acquisitions. This efficiency results because the LU decomposition of sparse impedance matrices performed as a pre-computation is tractable nowadays while the wave field computation performed by forward/backward substitutions for thousands of right-hand sides (i.e., seismic sources) is quite efficient.

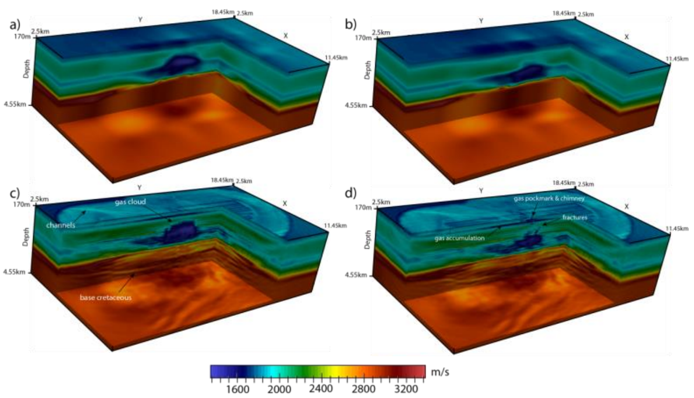

Figure 1: Seismic imaging of an oil field in the North Sea by reflection traveltime tomography (courtesy of BP) (a-b) and frequency-domain FWI (c-d). The volumes are parameterized by the vertical wavespeed. The reflection traveltime tomography model is used as a starting model for FWI. The figure highlights the tremendous resolution improvement achieved by FWI performed in the 3.5Hz-10Hz frequency band. This 3D imaging of an industrial dataset has been performed with the computational mean provided by the mesocentre SIGAMM hosted by Observatoire de la Côte d'Azur.

B.2 Lithospheric imaging from teleseismic data: the LITHOS code with application to CIFALPS

A 3D elastic time-domain FWI code (*LITHOS* code) suitable for lithospheric imaging from teleseismic data is developed in the framework of the PhD of Stephen Beller started in October 2013. We aim to image with a high-resolution (namely, in the 0.02Hz-1Hz frequency band) a lithospheric target located below a dense network of broadband stations from distant earthquakes located a few thousands kilometers away. Performing seismic modeling from the sources to the stations in a 3D global earth models with full waveform modeling engines such as the spectral element method (Komatitsch, 2002) would be prohibitively computationally expensive in the 0.02Hz-1Hz frequency band. To overcome this computational burden, we split the seismic modeling in two steps: first, we compute 3D full wave fields in an axi-symmetric global earth with the AxiSEM code (http://seis.earth.ox.ac.uk/axisem/) [1] and store the resulting 3D wave fields along the faces of the lithospheric target. Second, we use a grid injection technique (Monteiller et al., 2013), referred to as a full field/scattered field method, to perform the seismic modeling in the 3D lithospheric target from the solutions stored on his faces.

[1] this amounts to perform a few 2D simulations whose solutions are combined to form the 3D wave field.

Multiparameter reconstructions are performed for the P and S wave fields and density in the elastic isotropic approximation.

The *LITHOS* code is currently applied to the CIFALPS dataset (Zhao et al., 2015), a teleseismic dataset collected in the western Alps by a dense line of broadband stations (French PI: A. Paul (ISTerre)). The first results of the CIFALPS application are quite promising and reveal the geometry of the Ivrea body (Fig. 2). A more detailed quality control of the results is ongoing to assess which parts of the wave field contribute to the first-order to the tomographic reconstruction.

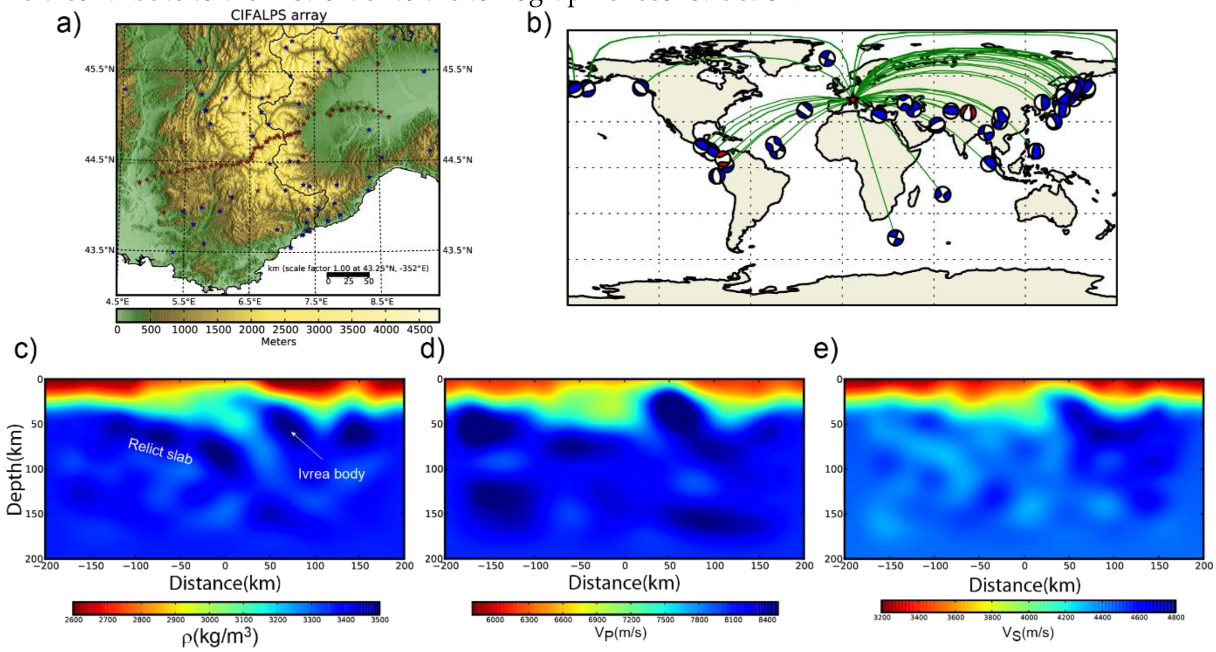

Figure 2: (a) CIFALPS station network. (b) Events selected for FWI. (c-e) Density, Vp and Vs models obtained by FWI (Figure from S. Beller, Geoazur).

B.3 Imaging of earthquake kinematics by FWI

We also want to tackle the source estimation problem, namely, the estimation of the spatio-temporal distribution of slip rate on a fault during earthquakes, assuming the subsurface properties known. Generally, this source inversion is performed by assuming 1D subsurface model in which Green's functions can be computed efficiently. However, the imprint of this assumption on the source characterization is still not well understood. To start investigating the source-structure coupling, we can afford today to perform full waveform modeling in 3D lithospheric models developed by traveltime or waveform tomography to perform earthquake kinematics imaging by linear waveform inversion[2]. Two numerical strategies are possible: (1) one can exploit the source-receiver reciprocity and pre-compute Green's functions treating the receivers as sources (GF approach). Then, the synthetic data can be computed by convolution of the Green's function with the source in virtue of the representation theorem. Since the convolution process is fast, global or semi-global optimization algorithms such as the very-fast simulated annealing algorithm can be used for inversion, while the computational burden mainly results from the Green's function computations from each station. (2) The second approach is more closely tied to the adjoint approach used for FWI: one can use the adjoint-state method to compute the gradient of the misfit function which requires two seismic modelings per inversion iteration, one to compute the wavefield using the slip rate as a boundary/initial condition and one to compute the adjoint wavefield by back-propagating the residuals from the stations (Somala, Ampuero and Lapusta, submitted at Gephysical Journal International[3]).

B.4. Global Earth imaging

As mentioned in the previous sections, recent advances in numerical methods for seismic wave propagation and high-performance computing have opened the door for high-resolution imaging of Earth's interior at crustal to global scales using earthquakes as natural sources. Phase inversions based on 3D seismic wave simulations[4] have been successfully applied at regional and continental scales (e.g., Zhu et al., 2015). However, applications of these full-wave tomographic approaches remained prohibitively expensive at the global scale until recently. A second difficulty results from the uneven illumination of the global Earth by seismic waves due to the lack of stations in the oceans. With the increase of computational facilities and the availability of massively-parallel 3D wave modeling engines, Bozdag et al. (2016, in prep.) developed the first global Earth model (mantle and crust) by adjoint tomography. This global model was obtained close of 15 inversion iterations with a selection of 253 global CMT events within the magnitude range $5.8 \leq Mw \leq 7.0$. A multiscale approach was implemented: the first eleven iterations were performed with numerical simulations having resolution down to 27 s combining 30-s body and 60-s surface waves with 90-min long seismograms. During the last three iterations, resolution was increased to 17s, including higher-frequency body waves as well as going down to 45s in surface-wave measurements with 180-min long seismograms assimilating all minor- and major-arc body and surface waves. Despite the moderate number of used earthquakes (253) and inversion iterations (15), the current tomographic model update shows a tantalisingly enhanced image of the Tahiti/Samoa plume as well as various other plumes and hotspots, such as Caroline, Galapagos, Yellowstone, Erebus, etc. Furthermore, The new velocity model also shows a clear improvement in slab resolution along the Hellenic and Japan Arcs, as well as subduction along the East of Scotia Plate, that was absent in the 3D starting model. A sample vertical cross-section across the Pacific super plume region is shown in Fig. 3. It is crucial to have accurate 3D images of the plume structures to understand the geodynamical and thermal history of the Earth and ultimately the other planets. Naturally, the next step in global-scale imaging is to account for the Earth anelasticity and anisotropy which will provide better constraints on the lithosphere and mantle interaction as well as the temperature and compositional variations, possible water content, for instance, in the upper-mantle transition zones, etc.

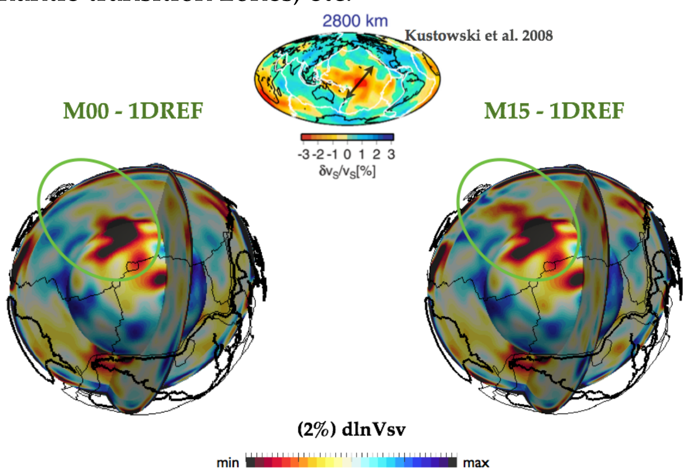

Figure 3: Vertical cross-sections of vertically polarized shear-wavespeed perturbations of the starting model 3D global mantle model S362ANI (Kustowski et al. 2008) with 3D crustal modal Crust2.0 (Bassin et al. 2000) on top (M00) and the global model after 15 conjugate-gradient iterations (Bozdag et al. 2016, in prep.). Perturbations are plotted with respect to the 1D reference model 1DREF (Kustowski et al. 2008). Horizontal ball shows the core-mantle boundary. Green ellipses are to highlight the enhancement of the Tahiti/Samoa plume in the Pacific after 15 iterations.

[3] http://web.gps.caltech.edu/~ampuero/publications.html#

C Future steps

C.1 Sedimentary basin imaging by frequency-domain FWI: the FFWI code

The FFWI application has been focused so far on the reconstruction of a first-order parameter (the vertical wave speed) in the VTI (vertically transverse isotropic) *visco-acoustic* approximation. However, a quality control of the data fit suggests that the effects of dispersion and absorption generated by attenuation have a significant footprint in the wave fields in particular when these latter propagated across a gas cloud. The ongoing work is three fold: *First*, we are currently extending the *FFWI* code to perform multi-parameter reconstruction for vertical and horizontal wave speeds, density and attenuation. This task is challenging because updating several classes of parameters which can have coupled footprints of different strength in the wave fields increase the ill-posedness of the inverse problem. Reconstructing parameters of different nature require second-order optimization algorithms such as the truncated Newton method, which can be demanding although our frequency-domain implementation should mitigate this computational burden (Operto et al., 2015). *Second*, we want to assess which problem size can be tackled today with direct solvers for imaging *visco-elastic* VTI subsurface medium, a key point for fluid characterization. Moving from the acoustic to the elastic approximation will increase the dimension of the linear system by a factor of at least 3. So far, we were able to solve linear system involving more than 17millions of unknowns with MUMPS. We hope in the future to tackle problems involving up to 50millions of unknowns taking advantage of a block-low rank version of MUMPS. This would probably allow us to perform elastic FWI at the sedimentary-basin scale and extend our acoustic inversion to deep crustal investigation for academic applications. The *third* extension deals with the implementation of various regularization techniques such as total variation to increase the "blockiness" of the reconstructed subsurface models and improve the resolution of the imaging accordingly.

The *FFWI* code has reached a maturity level such that it fulfills industrial standard. We are now reflecting on the best way of distributing this code to oil companies and contractors with an appropriate license. On the other hand, we also develop this code with the aim to provide to the academic community a pedagogic platform to learn about all of the methodological aspects of FWI. This code will be used to design computer-aided teaching during the summer school that we propose to organize during this project.

C.2 Lithospheric imaging from teleseismic data: application to ALPARRAY

Our project is to continue our investigation of this tomographic approach with an application to the European ALPARRAY project[5] whose aim is to determine the seismic structure of the whole Alpine region from a massive deployment of broadband stations by using a wide range of tomographic techniques including FWI (Figure 4). The deployment of the 80 French stations carried out by IPGS, ISTerre and Geoazur has started this year. We plan to start a PhD thesis in autumn 2017 once a sufficient number of teleseisms will have been recorded.

[5] http://www.alparray.ethz.ch/home

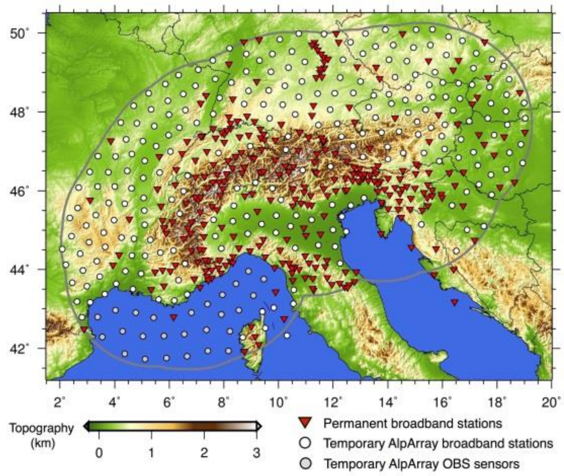

Figure 4: map of the ALPARRAY stations.

C.3 *Imaging of earthquake kinematics by FWI*

We would like to take advantage of our know-how on seismic modeling and FWI to adapt our codes to the source estimation problem and to combine the structure and the source imaging into an integrated investigation of a targeted area where a dense network of stations has been deployed. One possible target is the Chile subduction margin where took place the 2010 M8.8 Maule earthquake. A travel time tomography model of the area has been developed by Hicks et al. (2014). This model will be used as a starting model to perform FWI of regional earthquakes and refine the resolution of the tomographic model accordingly during the visit of A. Rietbrock (University of Liverpool) at Geoazur in 2016. From these travel time and FWI tomographic models, we can view to redefine the co-seismic slip of the Maule earthquake by waveform inversion using either the GF approach or the adjoint approach described in B3. This will provide a suitable framework to start investigating the trade-off existing between the source properties and the structure to fit seismic waveforms.

C.4. *Global Earth imaging*

Tracking seismic waves in the Earth

Unlike classical tomographic approaches, full-waveform inversion does not theoretically required identifying or selecting specific phases to be used. In the ideal case, the entire seismograms recorded by the three components should be used to dramatically increase the amount of data involved in the inversion and increase the resolution of the tomographic images accordingly. On the other hand to explore the possibilities and challenges to model every wiggle in seismograms, it is crucial to assess how the amplitude and phase of high-amplitude seismic phases (e.g., P, S, multiply reflected phases from surface and the core-mantle boundary, etc.) are reproduced by the new 3D models of Earth's mantle. Using recent global seismic models developed with either ray-theoretical (e.g., S40RTS developed by J. Ritsema et al.) or full wavefield (e.g., GLAD-M15; Bozdag et al. 2016, in prep.) methods, we propose to assess how well 3D modeling can explain the waveforms of major and more exotic seismic waves. In particular, the wave amplitudes are informative on whether long-wavelength scattering and multi-pathing are as important as seismic-wave attenuation generated by Earth's anelasticity. In addition, the problematic ray coverage at global scale due to uneven distribution of earthquakes and seismic stations is a major shortcoming in global imaging. Therefore we propose to keep track of the evolution of waveform fits from teleseismic paths over inversion iterations and perform real-time forward modeling during global-scale inversions to test and demonstrate the sources in the earth interior of the seismic anomalies observed at the surface, such as the amplitude variations of multiple reflections from surface, reflected and refracted phases from upper-mantle discontinuities and CMB (core-mantle boundary), waveform perturbations caused by large plumes. These detailed wavefield analysis should lead to an improved interpretation of seismic tomographic images and link the observations to the composition and dynamical structure of Earth's interior as well as defining better strategies for global waveform inversions.

High-frequency deep target-oriented imaging: application to the D″ layer

Another restriction in global-scale full-waveform inversions is the minimum period of simulations considering that the computational cost is not affordable or feasible below a 5s period. However, simulations at around 1 Hz is desirable to better understand the effect of smaller-scale heterogeneities on seismic waveforms. For instance, imaging the heterogeneities in the D'' layer that generate strong seismic anomalies observed at the surface is a quite topical issue in the geophysical community. Indeed, the D'' prime region, which forms a 200km-thick layer in the lower mantle on top of the core-mantle boundary, is thought to be the region where the superplumes originate (Lay and Garnero, 2004). Therefore, we propose to adapt newly developed hybrid-methods for lithospheric studies from teleseismic data (see section dedicated to the ALPARRAY project) to the high-frequency investigation of deeper targets such as the D″ layer. Our aim is to perform high-frequency modeling of PKP precursors that are generated by small-scale heterogeneities in the D″ region and back-propagate with adjoint methods these wavefield perturbations in the Earth interior to image these heterogeneities.

From a methodological viewpoint, a key difference with the target-oriented approach implemented for lithospheric imaging from teleseismic date (see previous section) results because the target is not anymore located below the network of stations. Therefore, the wavefield computed in the deep target after model alteration need to be propagated up to the surface at the station location. As for the wavefield propagation from the earthquake positions to the target, we shall use the AxiSEM code to propagate the target wavefield up to the surface. The grid injection technique to perform this target-oriented modeling is described in Masson et al. (2014).

References:

- Komatitsch D., Ritsema J. and J. Tromp, The Spectral-Element Method, Beowulf Computing, and Global Seismology, *Science*, 298(5599), pages 1737—1742, 2002.
- Hicks, S. P., Rietbrock, A., Ryder, I. M., Lee, C. S., & Miller, M. (2014). Anatomy of a megathrust: The 2010 M8. 8 Maule, Chile earthquake rupture zone imaged using seismic tomography. *Earth and Planetary Science Letters*, *405*, 142-155.
- T. Lay and E. Garnero, Core-Mantle Boundary structures and processes, Geophysical Monograph series, American Geophysical Union, 2004.
- Y. Masson, P. Cupillard, Y. Capdeville and B. Romanowicz. On the numerical implementation of time-reversal mirrors for tomographic imaging, *Geophysical Journal International*, 196, pages 1580—1599, 2014.
- Monteiller, V., Chevrot, S., Komatitsch, D. and Tromp, J. A hybrid method to compute short period synthetic seismograms of teleseismic body waves in a 3-D regional model, *Geophysical Journal International*, 192(1), pages 230—247, 2013.
- S. Operto, A. Miniussi, R. Brossier, L. Combe, L. Métivier, V. Monteiller, A. Ribodetti and J. Virieux. Efficient 3D frequency-domain mono-parameter full-waveform inversion of ocean-bottom cable data: application to Valhall in the visco-acoustic vertical transverse isotropic approximation, *Geophysical Journal International*, 202(2), pages 1362-1391, 2015.

- S. N. Somala, J. P. Ampuero and N. Lapusta, Finite-fault source inversion using adjoint methods in 3D heterogeneous media, submitted to the Geophysical Journal International, available at https://web.gps.caltech.edu/~ampuero.
- J. Virieux and S. Operto, An overview of full waveform inversion in exploration geophysics,J. Virieux and S. Operto, *Geophysics*, 2009, 74(6), pages WCC1-WCC26, 2009.
- L. Zhao, A. Paul, S. Guillot, S. Solarino, M. G. Malusa, T. Zhang, C. Aubert, S. Salimbeni, T. Dumont, S. Schwarz, R. Zhu and Q. Wang, First seismic evidence for continental subdiction beneath the western Alps, *Geology*, 43(9), pages 815—818, 2015.
- H. Zhu, E. Bozdag and J. Tromp, Seismic structure of the European crust and upper mantle based on adjoint tomography, *Geophysical Journal International*, 201(1), pages 18—52, 2015.

D. International collaborations

FFWI development and application

P. Amestoy, A. Buttari, J.-Y. L'Excellent, T. Mary. MUMPS team (ENSEEIHT – IRIT – INRIA Lyon).

L. Métivier, ISTerre/LJK, Grenoble.

Global scale imaging

J. Tromp (Princeton University)

D. Komatitsch (Laboratoire de Mécanique de Marseille). Seismic wave modeling with SPECFEM code.

J. Rietsema (University of Michigan)

E. List of people involved in the project

Permanent

Ebru Bozdag	Assistant Professor, UNSA, Geoazur	Global earth imaging
Bertrand Delouis	Professor, UNSA, Geoazur	Source imaging
Jean-Xavier Dessa	Assistant Professor, UPMC, Geoazur	Teleseismic FWI
Stéphane Operto	CNRS DR2, Geoazur	FFWI, teleseismic FWI
Alessandra Ribodetti	IRD CR1, Geoazur	FFWI, Summer school
Anthony Sladen	CNRS CR1, Geoazur	Source imaging

Contact: operto@geoazur.unice.fr

Engineers

Alain Miniussi, Research Engineer, High-performance computing, OCA.

PhD

Stefen Beller, Geoazur.

F. Most significant publications of the team

- Q. Bletery, **A. Sladen**, **B. Delouis**, M. Vallée, J. M. Nocquet, L. Rolland and J. Jiang, A detailed source model for the Mw9. 0 Tohoku-Oki earthquake reconciling geodesy, seismology, and tsunami records, *Journal of Geophysical Research*, *Solid Ea rth*, 119(10), pages 7636-7653, 2014.
- **E. Bozdag**, J. Trampert and J. Tromp, Misfit functions for full waveform inversion d on instantaneous phase and envelope measurements, *Geophys. J. Int.*, 185(2), pages 845—870, 2011.
- **S. Operto**, **A. Miniussi**, R. Brossier, L. Combe, L. Métivier, V. Monteiller, **A. Ribodetti** and J. Virieux. Efficient 3D frequency-domain mono-parameter FWI of OBC data: application to Valhall in the visco-acoustic VTI approximation, *Geophys. J. Int.*, 202(2), pages 1362-1391, 2015.

- J. Virieux and **S. Operto**, An overview of full waveform inversion in exploration geophysics**,** *Geophysics*, 74(6), pages WCC1—WCC26, 2009.
- H. Zhu, **E. Bozdag** and J. Tromp, Seismic structure of the European crust and upper mantle based on adjoint tomography, *Geophys. J. Int.*, 201(1), pages 18—52, 2015.

I. Short CV of participants

Ebru Bozdag, Chaire d'Excellence at Geoazur since 2014; PhD from Utrecht University (2009); Postdoctoral Research Associate, then an Associate Research Scholar, at Princeton University (2009-2014). She specializes on global seismology, 3D wave simulations and full-waveform inversion. Collaborator (2013-2014) and the co-I (2015-2016) of the INCITE Awards of Oak Ridge National Lab to run global full waveform inversions on their "Titan" system and the co-I of the CAAR program (2015) to continue global inversions on Oak Ridge's next generation supercomputer "Summit" to be ready by 2018.

Bertrand Delouis, Professor UNSA, Earthquake seismologist, Responsible of the Observatory center at Geoazur, 54 referred publications.

Jean –Xavier Dessa, Assistant Professor UPMC, Expert in seismic modeling & imaging. PI of the GROSMARIN project in the Ligurian basin, 18 referred publications.

Stéphane Operto, CNRS senior research scientist. Expert in seismic modeling & imaging. Co-PI of the SEISCOPE consortium (2006-2013). Responsible of the computing center at Geoazur. Associate editor of Geophysics. 62 referred publications. Award: 2005 EAGE Louis Cagniard Award, 2008 SEG best Geophysics paper award, 2014 SEG best Geophysics paper award (honorable mention).

Alessandra Ribodetti, IRD research scientist. Expert in seismic modeling & imaging. Involved in SEISCOPE and SISTEUR projects, 22 referred publications.

Anthony Sladen, CNRS research scientist, Earthquake seismologist, 24 referred publications.