A high-resolution seismic survey across the Balmuccia Peridotite, Ivrea Zone, Italy – Project DIVE

Introduction

The Ivrea Verbano Zone (IVZ) is one of the most complete crust–upper mantle geological references in the world, and the Drilling the Ivrea-Verbano zone project (DIVE) aims to resolve the uncertainties below this area. Geophysical anomalies detected across the IVZ indicate that dense, mantle-like rocks are located at depths as shallow as ca. 1-3 km (Scarponi et al. 2020, 2021). Thus, within DIVE several geological, geochemical and geophysical studies are planned, including the drilling of a 4 km deep borehole that will penetrate the Balmuccia Peridotite (Val Sesia, Italy), a peridotite body that outcrops in the IVZ. The objective of this borehole is to approach, and possibly cross, the crust–mantle transition zone, and provide for the first time geophysical in-situ measurements of the deepest rocks of the IVZ.

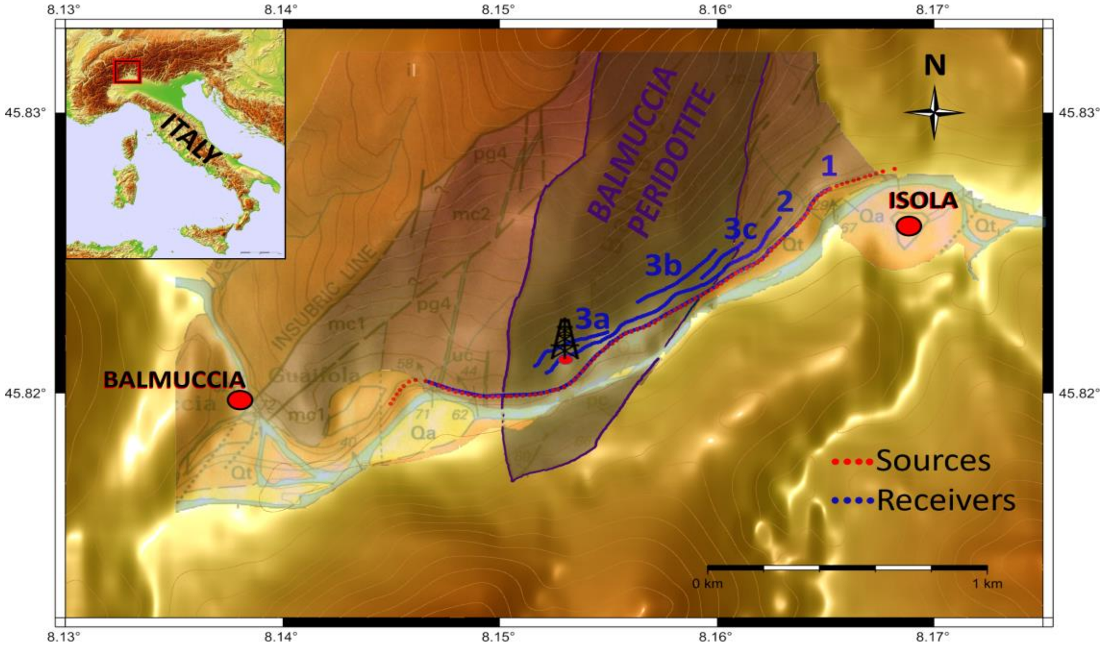

Figure 1 *Digital Elevation Model of the study area between Balmuccia and Isola, with overlaid geological features (modified from Quick et al. 2003), plausible drill site and position of receivers and sources. Numbers 1, 2 and 3 indicate the three sub-parallel lines. Lines A, B and C denote the position of the three tomographic profiles.*

One of the primary requirements before drilling is a seismic site characterization, to define with precision the correct positioning and orientation of the borehole, to assess potential drilling hazards and to allow for the spatial extrapolation of the borehole logs. For that goal, two joint geophysical surveys were performed in October 2020 in a collaboration between GFZ Potsdam, Université de Lausanne and Montanuniversität Leoben: (1) a deep seismic survey performed by GFZ Potsdam, entitled SEismic imaging of the Ivrea ZonE (SEIZE), consisting of two approximately orthogonal 15 km-long seismic lines, that aim to resolve the deeper structure of the IVZ in the area, and (2) a smaller seismic survey at the proposed drill site, entitled High-resolution SEismic imaging of the Ivrea ZonE (HiSEIZE), geared towards providing high-resolution seismic images of the uppermost few km. In this study, we focus on the HiSEIZE data.

The area of study is characterized by high-velocity crystalline rocks, which imposes several challenges for reflection seismology: Lithologic impedance contrasts in crystalline crust are usually weaker, the spatial coherence of reflections from faults and fractures is quite limited, steep dips are predominant, and the strong contrast between the weathering layer and the crystalline basement impedes the penetration of the wavefield generated by the source. These problems must be addressed by applying processing approaches that differ from classical imaging of sedimentary structures.

This project will not only provide site characterization for the DIVE project, but also contribute to understanding the structure of the Balmuccia Peridotite, its changes in depth and its relationship with the crustal-mantle transition. Here we present preliminary results of this ongoing project.

Seismic Acquisition

The HiSEIZE survey (Figure 1) was performed with a fixed spread of three sub-parallel lines spaced 50-80 m apart. Line 1 consists of 160 3C-sensors: 80 3C-accelerometers and 80 3C-4.5Hz-geophones. They were interleaved every ca. 11 m, following a local route that connects the towns of Balmuccia and Isola. Lines 2 and 3 encompass 200 10 Hz-vertical-geophones, deployed inside a local quarry every ca. 10 m. Complicated topography made the deployment of Line 3 a challenge, thus divided into 3 sub-sections (Figure 1). A source line of 2.4 km was designed along the local route, with source points at 22 m spacing. A 17.000 kg vibroseis was utilized as a source, emitting a 10 s linear sweep (from 12 to 140 Hz) with 3 s listening time. The source was activated 4 consecutive times at each source point, allowing for vertical stacking to improve the signal-to-noise ratio of the data.

2D Traveltime Tomography

The first step in seismic processing is the identification and picking of the first breaks. These wavefields are generally useful to obtain a first approximation of the velocities that characterize the near-surface. First break times were obtained from Line 1 (Figure 2a), used later as input for SIMULR16, a traveltime tomography program developed as an upgrade of the SIMULPS package (Bleibinhaus and Gebrande 2006).

SIMULR16 employs a linearized damped least squares inversion scheme for perturbing an initial velocity model. To avoid a biased initial velocity model with known velocities or geological structures, a grid refinement workflow was adopted for this project. This workflow consists of starting the inversion with a very simple cake-layered initial velocity model, which is defined by a very coarse node grid. The velocity model obtained after a first inversion is resampled with a denser node grid and later used as the new initial velocity model. This process is repeated for different node grid configurations until the velocity model obtained explains the data with a small residual, defined as the Root Mean Square (RMS) of the difference in time between the observed and inverted traveltimes.

For this project, the initial velocity model was defined in two dimensions by x and z grid nodes. The spacing between these started as 400 m and 100 m respectively (400 m x 100 m node grid) whereas the subsequent inversions were performed with 200 m x 50 m, 100 m x 25 m and finally 40 m x 10 m node grids. The results obtained for the latter were considered as the final velocity model, showing a residual RMS of 4 ms (Figure 2b). Further inversions with denser node grids did not produce a significant improvement of the results.

Seismic Processing

The presence of high-velocity crystalline rocks and sub-vertical structures throughout the study area (Liu et al. 2021) make seismic processing challenging. Important processing steps applied include:

- Generation of a high-resolution near-surface velocity model through traveltime tomography for subsequent refraction statics and velocity model building.
- P- and S-wavefield separation,
- Pre-Stack Depth Migration (PSDM)

The absence of continuous reflections did not allow for the application of a typical velocity analysis, such as semblance velocity analysis. Thus, traveltime tomography was used as the main tool for generating a velocity model that allowed for the application of refraction statics correction. In addition, it was used at a later stage as a velocity model for PSDM.

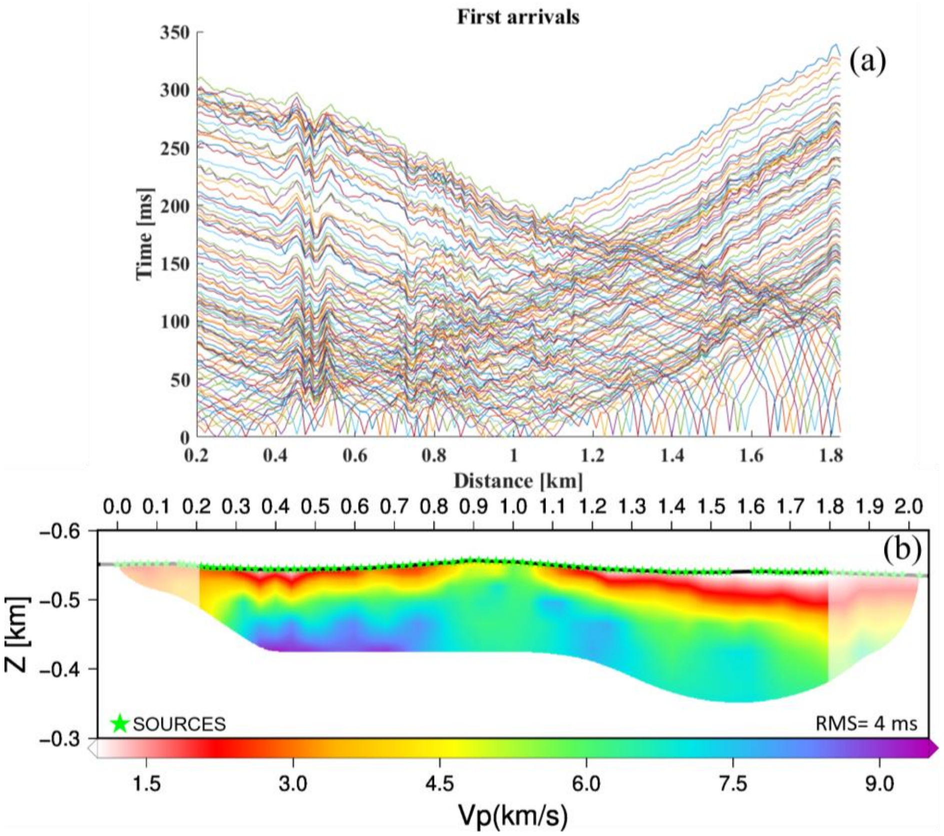

Figure 2 *(a) Plot of traveltimes used as input for SIMULR16 and (b) tomographic result for Line 1. Scale x:z = 1:2.*

Direct P-wave and S-wavefileds present throughout the data require the application of filters to separate and remove them from the desired reflected wavefields. The process used for the separation of the direct P-wavefield consists of:

- Align the first breaks to a defined time datum (datum = 100 ms)
- Calculate an alpha trim mean filter (traces per window = 9, trim percentage = 33%)
- Subtract the calculated filter from the data
- Restore the traces to their original positions in time

The same approach was applied for the direct S-wavefield separation. For this case, the S-wave “picks” were obtained by multiplying the first break times by a ratio of 1.7 ($V_p \approx \sqrt{3} V_s$) and then manual adjustments were made where necessary. Figure 3a shows a shot gather after the application of this process.

Conventional CMP-processing workflows find major difficulties when applied to data acquired in a crystalline environment. Shot gathers in said environments usually do not show clear signals with good coherency and hyperbolic shape. Thus, the CMP-sorting does not improve this situation making its benefits not very useful in this case. Therefore, the concept of pre-stack migration is more appropriate to apply to seismic data from a crystalline environment. Consequently, this approach was considered for this project by applying PSDM with no previous CMP-processing. To account for the crookedness of Line 1 a 3D PSDM was applied. Figure 3b shows an example after this process, where some features show good correlation with what can be observed in the tomographic results.

Conclusions

- Results from the traveltime tomography can outline the structure of the Balmuccia Peridotite for the first 150 m of the subsurface.

- The processing approach for removing direct P and S-wavefields is successful in removing their signature in most of the data.
- First PSDM results show good correlation with the tomographic results, outlining sub-vertical structures possibly associated with the peridotite boundaries and faults within it.

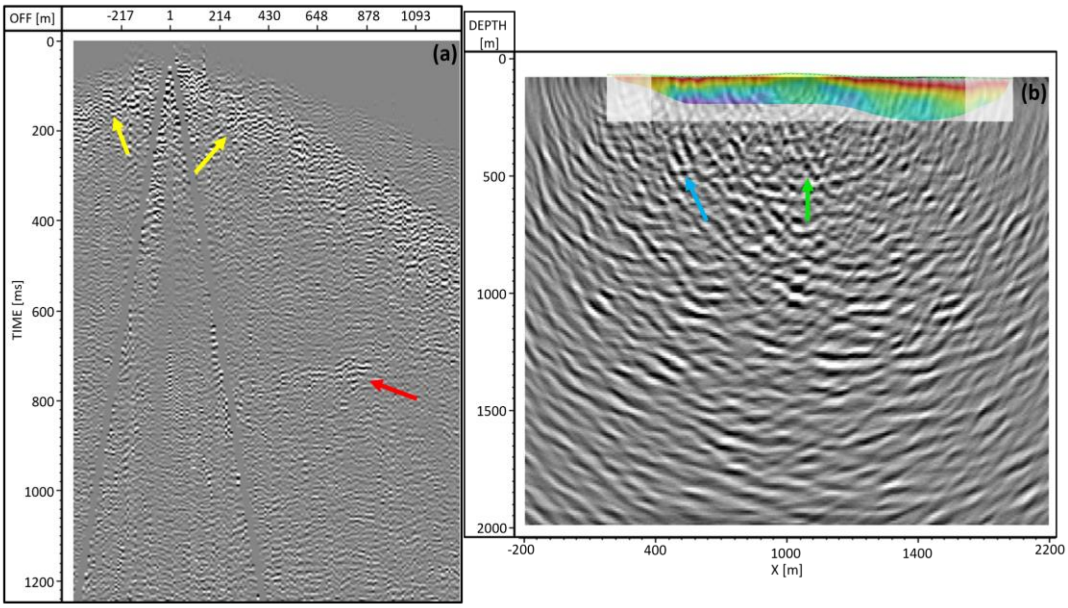

Figure 3 *A shot gather after removing direct P and S-waviefields is depicted in (a), with reflected refractions marked with yellow arrows and a possible reflector with a red arrow. (b) Preliminary results of a PSDM overlaid with the tomographic profile (see Figure 2b). Marked with a blue arrow is the possible boundary of the Balmuccia Peridotite, which correlates with the tomographic results. The green arow depicts a possible fault.*

Acknowledgements

We thank: GFZ Potsdam for allowing us to piggy-back their survey (SEIZE). The Geophysical Instrument Pool Potsdam (GIPP) for providing 80 3C-geophones and 80 recorders (DATA-CUBE3). University of Lausanne for the GPS data collection and processing, and their support during the seismic survey. Natalia Banasiak and Jean-Paul Bergoeing for their help in the field.

References

Bleibinhaus, F., and Gebrande, H. (2006). Crustal structure of the Eastern Alps along the TRANSALP profile from wide-angle seismic tomography. Tectonophysics, 414(1-4), 51-69.

Liu, Y., Greenwood, A., Hetényi, G., Baron, L., and Holliger, K. (2021). High-resolution seismic reflection survey crossing the Insubric Line into the Ivrea-Verbano Zone: Novel approaches for interpreting the seismic response of steeply dipping structures. Tectonophysics, 816, 229035.

Quick, J. E., Sinigoi, S., Snoke, A. W., Kalakay, T. J., Mayer, A., and Peressini, G. (2003). Geologic map of the southern Ivrea-Verbano Zone, northwestern Italy. US Geological Survey.

Scarponi, M., Hetényi, G., Berthet, T., Baron, L., Manzotti, P., Petri, B., ... and Müntener, O. (2020). New gravity data and 3-D density model constraints on the Ivrea Geophysical Body (Western Alps). Geophysical Journal International, 222(3), 1977-1991.

Scarponi, M., Hetényi, G., Plomerová, J., Solarino, S., Baron, L., and Petri, B. (2021). Joint seismic and gravity data inversion to image intra-crustal structures: the Ivrea Geophysical Body along the Val Sesia profile (Piedmont, Italy). Frontiers in Earth Sciences. Earth Sci, 671412.