High-resolution imaging of basin-bounding normal faults in the Southern Apennines seismic belt (Italy) by traveltime and frequency-domain full-waveform tomography

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SUMMARY

We apply a two-step seismic imaging flow by combined first-arrival traveltime and frequency-domain waveform tomographies to dense wide aperture data collected in the Val d'Agri basin (southern Italy). A large wavelength Vp model determined by first-arrival traveltime tomography is used as a starting model for waveform tomography. The multiscale waveform tomography consisting of successive inversion of increasing frequencies allows to progressively reconstruct the short wavelengths of the velocity model, providing valuable information on the Quaternary basin and on range-bounding normal-faulting systems.

Introduction

The Val d'Agri is a Quaternary basin located in the Southern Apennines thrust-and-fold belt (Italy). Despite morphotectonic investigations carried out in the last decade, the geometry and kinematics of the fault systems controlling the recent tectonics of the basin are still debated. Two conflicting interpretations in the literature defend a SW- or NE-dipping normal faulting system bordering the north-eastern and the south-western margins of the basin respectively (for a review, Maschio et al., 2005). Many uncertainties on the shallow architecture of the basin and of the range-bounding fault systems remain despite the intense commercial reflection profiling carried out in the area. Indeed, reflection profiles yield poor stack sections beneath the Quaternary basin (Shiner et al., 2004) because highly variable topography and near-surface geology together with an extreme structural complexity hamper imaging by conventional reflection seismics. In order to assess the potentialities of innovative imaging tools in this complex area, ENI E&P and Enterprise Oil Italiana carried out non-conventional dense wide-aperture seismic surveys (Dell'Aversana, 2003). The availability of dense wide-aperture data in the Val d'Agri area provides a unique opportunity to get new insights on the basin structure by using advanced inversion techniques for shallow crustal imaging.
In this study, we apply a seismic imaging flow, which combines first-arrival traveltime tomography with frequency-domain full-waveform tomography, to a dense wide-aperture profile about 18 km long crossing the Agri basin. Recent successful applications demonstrated the efficiency of this exploration strategy to investigate complex onshore thrust-and-fold structures (Ravaut et al., 2004) and steeply dipping faults (San Andreas Fault, Bleilbeinhaus et al., 2007). The two-step procedure starts determining multi-scale P-wave velocity images of the basin down to 1.5 km depth by a first-arrival traveltime tomographic technique specifically designed to image very complex velocity structures. The estimation of an accurate reference velocity macromodel is indeed a key prerequisite for the subsequent frequency domain full-waveform inversion, that allows to considerably improve spatial resolution of the velocity images with respect to traveltime tomography. Discrete frequency components of the data are iteratively inverted from low to high frequency values in order to progressively incorporate smaller wavelength components into the model.

The Method

The seismic imaging flow consists of a two-step inversion procedure. In order to determine an appropriate background velocity model for frequency-domain waveform inversion, we first inverted first-arrival traveltimes by a non-linear tomographic technique effective to image strongly heterogeneous media. The inversion procedure combines a multi-scale strategy and a nonlinear optimization scheme: (1) a succession of inversions is run by progressively refining the velocity grid and (2) at each inversion run the best-fitting model is searched by a mixed global random (Monte Carlo) and local (Downhill Simplex) search. This combination allows decreasing the computational cost, and strongly reduces the risk of falling trapped in secondary minima of the cost function by densely sampling the multi-parameter space (see Improta et al. (2002) for more detail).
The subsequent full-waveform inversion follows an iterative least-squares local optimization scheme based on the gradient method (e.g., Ravaut et al., 2004). Both the forward and inverse problems are performed in the frequency domain (e.g. Pratt et al., 1998). The wave propagation modelling in the visco-acoustic approximation is performed with the mixed-grid finite-difference method that provides both accurate and spatially-compact stencils (Hustedt et al., 2004). These stencils are suited for frequency-domain modeling based on direct solver which is the approach of choice for efficient 2D multi-source simulations. A preconditioned gradient method is used to solve the local optimization problem. The velocity perturbation $\delta\mathbf{m}$ is related to the conjugate of the data residual $\delta\mathbf{d}^*$ through the equation:

$$\delta\mathbf{m} = -\alpha \nabla_m E = -\alpha\, \mathbf{J}^T \delta\mathbf{d}^*$$

where $\nabla_m E$ is the gradient of the cost function, $\mathbf{J}^T$ is the transposed Jacobian matrix and α is a step length controlling the amplitude of the perturbations. Thanks to the source-receiver reciprocity principle, the gradient of the cost function can be estimated by only two waveform modellings per shot providing the incident and the back-propagated residual wavefields respectively (Tarantola, 1984). The gradient is preconditioned by the diagonal terms of the approximate Hessian matrix (Shin et al., 2001). The inversion procedure follows an iterative multiscale approach. We inverted each frequency component independently proceeding from the low to the high frequencies. The process is iterated non-linearly using the final model of a given frequency inversion as the starting model for the next frequency inversion. This hierarchical inversion strategy allows to progressively incorporate finer wavelengths into the model, hence mitigating the strong non-linearity of waveform inversion. In this application, model perturbation is limited to the P-wave velocity (density and attenuation are constant).

Traveltime Tomography

The two-step imaging flow was applied to a dense wide-aperture profile collected in the Val d'Agri area by Enteprise Oil Italiana and ENI E&P in 1999 (Dell'Aversana, 2003). The acquisition layout consisted of a fixed array of 201 receivers, with a 90 m spacing, that recorded 284 shots fired with an average 60 m interval.

Traveltime tomography was applied to about 9000 first arrivals handpicked on 113 common shot panels (CSP) up to 7 km offsets. First-arrival picking at larger offset is complicated by evident shadow zones (Figure 1), which suggest significant velocity inversions, and by an overall low signal-to-noise ratio for far offset traces on many CSPs. Resolution tests showed a rapid decrease of the resolution depth by progressively refining the velocity grid. This is caused by high-velocity (Vp≅5 km/s) shallow shelf limestones forming the basin substratum, which overlay low-velocity regions (Vp≅3.5 km/s) corresponding to basinal terrains (Figure 2). This velocity structure makes the first-arrival rays sample the shallow high-velocity carbonates only. The traveltime-inversion model obtained after six inversion runs was used as starting model in the waveform inversion (Figure 2). We feel that this model provides the best compromise between kinematic accuracy (a key element to avoid cycle-skipping artefacts during the full-waveform inversion) and smoothness. A resolution depth of 800-1200 m makes this model suitable for waveform modelling of relatively shallow phases (i.e. PP vertical reflections with two-way-times lower than 0.6-1.0 s).

Frequency-domain waveform inversion

Waveform inversion pre-processing aimed at improving data quality and at mitigating amplitude variations due to source variability, as well as amplitude variations with offset caused by attenuation, near-surface conditions and receiver-ground coupling. We applied the sequence of Ravaut et al. (2004) including whitening, band-pass filtering, trace editing, and muting plus offset windowing to remove late-arriving phases not included in the model (Figure 1).

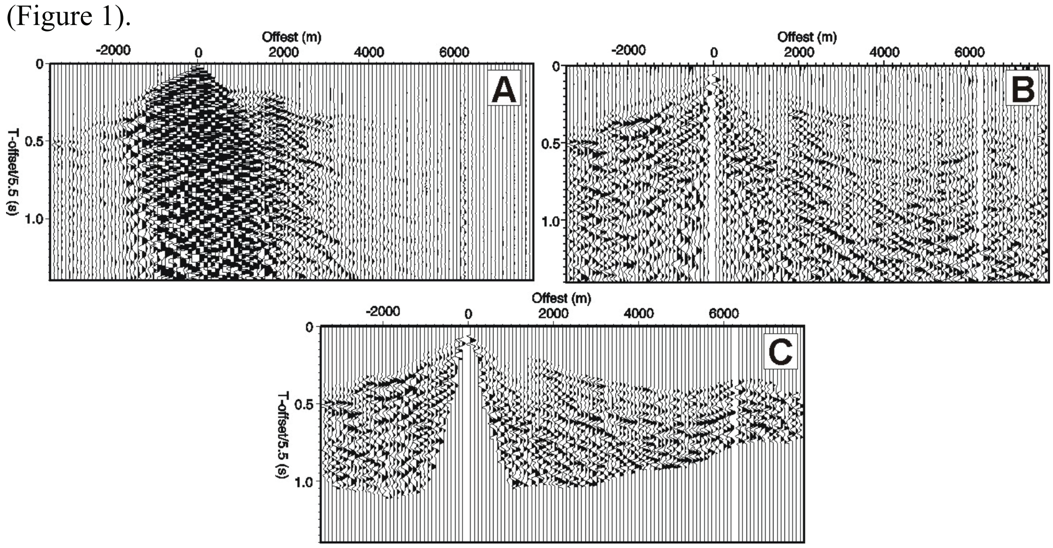

Figure 1: Representative example of CSP gather. Raw data (A),after waveform inversion pre-processing (B), after muting (C). Traces in plots B and C are normalized for graphic purpose.

A sub-dataset of 62 good-quality CSPs not affected by strong variations in source size was inverted. Seven frequencies ranging from 4.4 and 19.5 Hz were inverted successively and 15 iterations were performed per frequency. We run several inversions modifying the thickness of the near-surface layer kept fixed to avoid near-surface instabilities and the damping (ε). The best results in term of inversion convergence, cost function reduction and model features were obtained setting ε to 0.003 and keeping fixed the velocities down to 75 m depth. The improvement of spatial resolution with respect to the traveltime inversion model is evident down to 600-700 m depth even at low frequency (i.e. 5.4 Hz) (Figure 2).
Waveform inversion yields valuable information on Quaternary basin structure. The basin infill corresponds to low-velocity deposits reaching a thickness of 500 m, in agreement with published well data (Dell'Aversana, 2003). The basin appears divided in two sectors. Vp values around 3 km/s characterize the eastern and deeper part of the basin and well correlate with cemented slope breccias. The shallow and central-western sectors show lower Vp values (Vp=1.5-2.0 km/s), which can be interpreted as more recent fluvio-lacustrine deposits. The carbonate substratum shows a complex shape, and steep dipping high-velocity zones at both basin edges highlight high-angle normal-fault systems (Figure 2, models on the rights).

Conclusion
We presented preliminary results of full-waveform inversion of dense wide-aperture data from a profile recorded in the Val d'Agri Quaternary basin. Although we inverted only a sub dataset, an evident improvement of spatial resolution has been achieved with respect to traveltime inversion model. These preliminary models are locally confirmed by subsurface data and yield a reliable image of the basin. Our future effort will focus on the inversion of a wider data set and on model reliability assessment.

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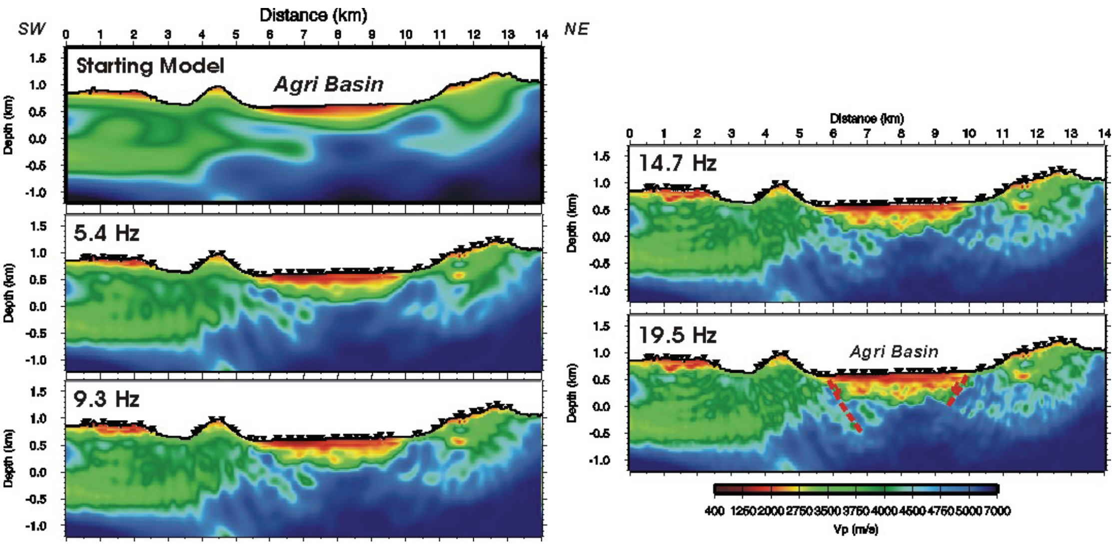

Figure 2: Vp images obtained by full-waveform inversion at four frequency components. The traveltime inversion model is show in the upper panel on the left. Note the improved spatial frequency content of images. Sources position is outlined by solid triangles.

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