Depth and morphology of reflectors from the non-linear inversion of arrival times and waveform semblance data. Part II: modelling and interpretation of real data acquired in Southern Apennines, Italy

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ABSTRACT

In order to retrieve a 2D background velocity model and to retrieve the geometry and depth of shallow crustal reflectors in the Southern Apennines thrust belt a separate inversion of first arrival traveltimes and reflected waveforms was performed. Data were collected during an active seismic experiment in 1999 by Enterprise Oil Italiana and Eni-Agip using a global offset acquisition geometry. A total of 284 on-land shots were recorded by 201 receivers deployed on an 18 km line oriented SW–NE in the Val D’Agri region (Southern Apennines, Italy).

The two-step procedure allows for the retrieval of a reliable velocity model by using a non-linear tomographic inversion and reflected waveform semblance data inversion. The tomographic model shows that the P wave velocity field varies vertically from approximately 3 km/s to 6 km/s within 4 km from the Earth’s surface. Moreover, at a distance of approximately 11 km along the profile, there is an abrupt increase in the velocity field. In this zone indeed, an ascent from 2 km depth to 0 km above sea level of the 5.2 km/s iso-velocity contour can be noted. The retrieved velocity can be associated with Plio-Pleistocene clastic deposits outcropping in the basin zone and with Mesozoic limestone deposits. The inversion of waveform semblance data shows that a P-to-P reflector is retrieved at a depth of approximately 2 km. This interface is deeper in the north-eastern part of the profile, where it reaches 3 km depth and can be associated with a limestone horizon.

INTRODUCTION

Seismic imaging of complex geological structures is often a difficult task due to the presence of rough topography, sharp near-surface velocity variations and strong lateral heterogeneity of the velocity field at all depths. In particular, this is the case for the Apenninic thrust belt regions in southern Italy, where the complexity of the geological medium generally prevents the acquisition of high-quality seismic data. This is reflected by difficulties in retrieving accurate velocity models and the geometry of seismic discontinuities, which are utilized by oil companies for exploration purposes.

In 1999 the Enterprise Oil Italiana company performed a ‘Global Offset’ acquisition survey in the Val d’Agri area, Southern Apennines (Italy), along an 18 km line (Dell’Aversana et al. 2003) to investigate the feasibility of high resolution surveys within a thrust belt geological environment for industrial purposes. This acquisition technique is an innovative seismic methodology designed to acquire seismic data over an extended offset range. Standard seismic shots are recorded simultaneously by a conventional seismic layout and by densely spaced 3C stand-alone stations deployed over the whole range of available offsets. The advantage of such an
acquisition layout is that it allows the simultaneous collection of near vertical and wide angle reflection data using conventional sources enabling the retrieval of sub-soil information both from refracted/turning and reflected/converted arrivals. The analysis and interpretation of redundant data can provide accurate information on velocity distribution and interface geometries.

The seismic response of the Southern Apennines is highly variable, ranging from moderate to poor. It is controlled by a number of factors that are commonly acknowledged to limit seismic quality, such as extreme topographic variation, highly variable surface geology and complex structures, commonly characterized by strong lateral velocity variations. Previous geophysical studies revealed the extremely poor seismic response of the geological target when conventional processing (stack and post-stack depth migration) was used. Improta et al. (2002) have shown that the combined use of wide-angle and near vertical reflection data provide more advantages in the definition of good quality images compared to the use, in the inversion procedure, of only conventional near-vertical reflection data.

As shown by different authors, a useful tool to investigate velocity distribution in complex geological environments is first break seismic tomography, which enables the building of a smooth velocity model using first-P travel time pickings. Moreover, a well-refined knowledge of the 2D background velocity model is required in order to accurately model the reflected/converted arrivals at depth.

In order to obtain a reliable 2D smooth velocity model we inverted first arrival travel time picks using a non-linear tomographic method based on a Bayesian approach (Zollo et al. 2002).

The obtained velocity model was then used as a reference model to perform a non-linear inversion of the P-to-P reflected arrival times and semblance data in order to retrieve the morphology of the associated seismic reflector. The interface inversion method used was based on an iterative, non-linear inversion scheme that follows a two-step procedure to combine information from reflected traveltimes and waveform semblance data, as proposed by Vassallo and Zollo (2008).

Both of these inversion methods adopt a multi-scale strategy and non-linear inversion schemes permitting a wide exploration of the parameter space model.

Topography is included in both of the inversion procedures, so that no static correction is required as with standard reflection modelling tools. Finally, the interface inversion method does not require any particular data organization. This means that data organized in different ways can be used to perform the inversion (as shown in this paper, where common-midpoint (CMP) and zero-time move-out sections have been used to gather data).

The interface inversion method used can be considered as an alternative to the conventional migration techniques which, as many authors have shown, may fail in geological contexts such as the Southern Apennines, where strong lateral velocity variations are present at all scales and where the topography is so rough that accurate static corrections are required. Prestack-depth waveform processing, such as prestack depth migration or full waveform inversion, may provide useful inferences on the structure using as a background model the velocity model inferred from travelt ime inversion.

**METHOD**

First arrival travel times tomography

The used tomographic method allows one to obtain reliable 2D velocity models in complex geological environments from the inversion of first arrival travel times. The inversion strategy, proposed by Zollo et al. (2002), uses a non-linear optimization scheme and a multi-scale approach (Lutter et al. 1990).

The velocity model is parameterized by a regular grid of nodes where the P-wave velocity values are assigned. The method is based on the search for the maximum likelihood solution in the model parameter space, i.e., the space of possible values for P-velocity at nodes of the 2D grid. The forward problem is solved by using a ray tracing method based on a two-point ray-tracing shooting technique (Zollo et al. 2002). The velocity at any point of the medium is evaluated using a cubic-spline interpolating function.

The cost function of the inverse problem is constructed upon the natural logarithm of the a posteriori probability density function (pdf) using a Bayesian approach.

According to Zollo et al. (2002), the conditional pdf of the observed first arrival times (d≡[d_1, . . . , d_N]) is defined as:

$$p(d|m) = \text{const} e^{-\frac{E}{2\sigma^2}}$$

(1)

where m is the model parameter vector.

E in equation (1) is the cost function of the optimization problem computed as:

$$E = \sum_{i=1}^{N_N} \sum_{j=1}^{N_s} u_{ij} (t_{ij}^{obs} - t_{ij}^{calc})^2$$

(2)

where N_N is the number of sources, N_s is the number of observed arrival times for the jth source, and t^{obs} and t^{calc} are...
the observed and computed first arrival times. Finally, $\omega$ is the normalized data weighting factor inversely related to the uncertainty of the time picking measurement.

One main advantage of using the Bayesian approach is the possibility to introduce an a priori information on the model space and to compute the posteriori probability $p(m|d_0)$ for $m$, given an observed data vector $d_0$:

$$p(m | d_0) = \text{const} \cdot p(d_0 | m) \cdot \rho_1(m). \quad (3)$$

The constant in equation (3) is the pdf normalization factor. $\rho_1(m)$ is the prior probability of the model parameters, which represents the state of knowledge about the model space. In our case, the prior pdf $\rho_1(m) = 1$ for $m \in [m_{\text{prev}} - \Delta m, m_{\text{prev}} + \Delta m]$ and $\rho_1(m) = 0$ elsewhere. $m_{\text{prev}}$ is a vector composed by the velocity values interpolated from a velocity model obtained in a previous iteration using a coarser medium discretization and $\Delta m$ is an arbitrary assigned range.

The tomographic strategy consists in progressively increasing the grid nodes at which the model parameters are estimated. This strategy, known as the multi-scale approach (Bunks et al. 1995; Jin and Beydoun 2000) is, in principle, equivalent to a move from a low to a high wavenumber description of the velocity field. The solution found at the long wavelength scale of the problem is then recursively refined by using it as an initial solution at increasingly shorter scales (Bunks et al. 1995).

The search for the parameters that minimize the cost function is performed using the genetic algorithm (Goldberg 1989; Whitley 1994). Compared with other non-linear optimization methods (Monte Carlo, simulated annealing), this type of algorithm has shown to be very efficient and fast for a wide exploration of a multi-parametric model space (Sambridge and Drijkoningen 1992; Boschetti, Dentith and List 1996).

At a very early stage of the inversion process, no a priori information is introduced and the search is performed over a wide range of possible velocity values. For successive runs, when the medium is described by a larger number of grid nodes, the search is restricted within a velocity range that has smaller variations around the model estimated in the previous run.

In order to investigate the model resolution, a synthetic test was performed using a heterogeneous target model, the same acquisition layout used to collect the data and the same inversion scheme. This test was chosen to check the capability of both method and data to retrieve the main geometrical features appearing in the best fit model (e.g., extension, shape and amplitude of velocity anomalies).

In the paragraph ‘First arrival travel times tomography results’ the results of the synthetic test are presented.

Remarks on the reflection method

An innovative interface inversion method, based on the non-linear optimization of reflection waveform semblances and a multi-scale approach (Vassallo and Zollo 2008), was used to retrieve the depth and 2D morphology of reflectors. This method is based on a two-step inversion scheme, which combines the information from picked travel times and waveform semblance data. The general idea underlying the method is that reflected travel times provide long wavelength information about the interface morphology while more refined models can be retrieved by the waveforms semblance.

In order to retrieve the interface depth and geometry, a background, reference velocity model is required. In the present case, this model is obtained from the first-P arrival time inversion.

The reflector model is described by a 2D cubic-spline function and the parameters are the depths of the cubic-spline nodes, taking their horizontal position as fixed and equally spaced.

More details regarding the inversion method can be found in Vassallo and Zollo (2008).

APPLICATION TO REAL DATA: AGRI VALLEY

Data acquisition and organization

Data used in this study were collected in 1999, in the Val d’Agri region, Southern Apennines (Italy), along a profile oriented SW–NE (Fig. 1), using a Global Offset acquisition geometry. The seismic line was 18 km long, shots were spaced at 60 m intervals and a fixed array of 201 receivers, with a 90 m interval, was deployed (for a detailed description of the experiment see Dell’Aversana et al. 2003). This layout geometry allows for the acquisition of data with a wide range of offsets. Also, highly redundant near-vertical offset data as well as refracted and wide-angle reflected data can be jointly used to investigate the subsurface. Two different approaches to data organization and analysis were used. In order to identify first arrival travel times, data were organized in common shot panels while a common-midpoint (CMP) gathering was preferred in order to identify reflected phases, which provide information on the depth and geometry of deep discontinuities in the area.
First travel times were hand picked on seismic sections gathered as common shot panels. In order to ensure homogeneous data coverage, shots were chosen according to their position along the profile (Fig. 2) and 24 common shot panels were finally selected, showing a good signal to noise ratio and clear first arrivals. A representative common shot panels section, located in the NE part of the profile, is displayed in Fig. 3. The section was obtained using a zero-phase shift Butterworth filter in the range of 4 and 35 Hz, an automatic gain control (AGC) with a time window of 0.5 seconds and amplitude normalization. This common shot panel shows a high S/N ratio and clear first arrivals up to 4 km from the shot. We picked first arrivals, on this section, up to 12 km; beyond this limit first break information was lost in ambient noise. A weighted picking, computed as the reciprocal of the uncertainty in the travel time picks, was used in the tomographic inversion in order to take into account the uncertainty as a function of the distance from the source.

A dataset of approximately 3000 first arrival travel times picked on the 24 sections was used to perform the tomographic inversion, which was then used as a background velocity model for reflection phase modelling.

Reflections dataset

In order to identify reflected phases on seismic sections, the data were organized in common-midpoint sections (CMP) with a total of 180 CMP sections built and analysed. The used data processing flow included: zero-phase shift Butterworth filter in the range of 6 and 25 Hz, automatic gain control (AGC) with a time window of 0.5 seconds and amplitude normalization.

A standard NMO analysis was performed to identify reflection events on a section having a maximum offset of 1 km.

Figure 4 shows 12 CMPs arranged according to their position along the profile proceeding from the SW to the NE part. A reflection event is clearly detected at times in the range
1.5 and 2.0 seconds, proceeding eastwards and it was picked on 40 CMPs located in the NE part of the profile. The delay in the arrival time provides evidence for the complexity of the reflector and/or the propagation medium. Picked reflected times were used as a preliminary dataset in the first step of the interface inversion. The interface so obtained was used to compute theoretical reflected times which were used to build a zero-time move-out section (see the zero-time move-out paragraph) using all the seismograms. This procedure allowed for a better identification of the reflection event all along the analysed profile.

First arrival travel times tomography results

We applied the tomographic method described above to retrieve a 2D smooth velocity model for the Agri valley. In order to retrieve the final model, a series of 5 inversion runs was performed. Using the multi-scale approach, models described by 4, 9, 16, 56 and 224 velocity nodes were computed. The increase in the number of parameters corresponds to an increase in the spatial model sampling. For each run, the search for the maximum likelihood model was stopped when the cost function versus the iteration numbers approached zero within an arbitrary fixed threshold. A total of approximately 73 000 models were explored for the model defined by 14 nodes in the x-direction and 16 in the z-direction (224 parameters). The mean computation time needed to perform 1 iteration using approximately 3000 data for a model described by 14 \( \times \) 16 nodes, was approximately 7 hours on a Linux based PC, with a Pentium IV 3 GHz processor.

An increase in the model roughness was observed, moving from a small to a high number of parameters corresponding to the smaller wavelength explored. The increase in the number of model parameters generally corresponds to a fit improvement. In order to estimate the statistical significance of the fit improvement, the corrected Akaike information criteria parameter was estimated. This criterion was first introduced by Akaike (1974) for model selection and then modified by Cavanaugh (1997). The model providing the minimum value of the corrected Akaike information criterion parameter computed as:

\[
AIC_C = N \ln (2 \pi E) + \frac{N(N + P)}{N - P - 2}
\]

was selected. In equation (4), \( E \) represents the misfit value, \( N \) is the number of data and \( P \) is the number of parameters. The search for the tomographic model having the minimum corrected Akaike information criterion value corresponds to the selection of the solution that represents the best compromise between the goodness of the fit and the simplicity of the models. The values obtained for the models described by 7 \( \times \) 8 nodes (56 parameters) and 14 \( \times \) 16 nodes (224 parameters) were 175 and 222 respectively. According to the corrected Akaike information criterion, the model described
Figure 4 CMP sections between 14 and 15 km (a) and between 17 and 18 km (b) along the profile. All these CMPs show the reflected phase identified. Ground rolls are also evident in these sections, with a waveform different from that of the reflected event identified.

by 7 × 8 parameters was chosen as the final model (Fig. 5). With this, anomalies with a minimum wavelength of 1 km in depth and approximately 2.5 km in horizontal direction were retrieved.

The final model shows a variability of P wave velocity ranging from approximately 3 km/s to 6.5 km/s. A sharp lateral velocity change at a distance of approximately 11 km along the profile was observed, where the 5.2 km/s iso-velocity contour rise from 2 km deep to approximately 0 km in depth. In order to investigate the model resolution, a fixed geometry test (e.g., Zollo et al. 2002) was performed. The synthetic test consists in performing a number of inversions using synthetic data computed in the acquisition layout of real data and for a velocity model, which reproduces the main geometrical features observed in the model obtained from the inversion of real data. In particular, the test was performed in order to check the capability of the inversion method to retrieve the shape and the spatial extension of the sharp velocity increase found at a distance of approximately 11 km along the profile. The Fig. 6(a) panel shows the synthetic model used to compute the synthetic data. The retrieved model (Fig. 6b panel) is described by 7 × 8 nodes and it efficiently reproduces the ascent of the 5.2 km/s iso-velocity contour either in its spatial extension or position.
Non linear interface inversion results

In order to model the identified reflected phase in the range 1.5–2.0 sec. two-way travel time, the non linear data inversion was performed in a two-step procedure, as in Vassallo and Zollo (2008).

In the beginning, the inversion was performed using the dataset picked on 40 CMPs, the velocity model retrieved by

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travel time tomography and the reflected travel time residuals in order to define a L^2 norm cost function. All data acquired was then reorganized in a unique zero-time move-out section (see the ‘Zero-time move-out section’ paragraph).

A dataset made up of approximately 500 picks was used for reflected traveltime inversion in order to retrieve a preliminary reflector model, as shown in Fig. 7.

The latter was located in the NE part of the profile, between 2 and 3 km below sea level and appears to deepen in the NE direction according to the travel times observed. This model shows a minimum of the L^2 norm cost function, computed as a RMS value, of approximately 0.08 sec.

Zero-time move out section

The interface retrieved using the 500 picks dataset (Fig. 7a), was extrapolated along the whole profile (dashed line in Fig. 7a) and theoretical travel times were computed for each source-receiver pair for a reflected phase originating from the whole interface using a ray-tracing algorithm. These travel times were used to build a zero-time move-out section, defined as a section in which each seismogram is time-corrected for the computed reflection travel time of a given interface model (Impronta et al. 2002).

This procedure is similar to a move-out scheme but uses a laterally inhomogeneous background medium and a rough interface. In case of negligible errors in the location and shape of the interface, the modelled reflection event should align at zero seconds and should show a lateral coherence on the moved-out panels. Therefore, the reliability of the determined interface can be verified by measuring the alignment of the reflection events on the moved-out gathers by a horizontal stacking of the traces.

The phase alignment can be quantitatively verified by performing a semblance analysis on this section, where the presence of a reflected phase should correspond to a maximum of the semblance function at 0 seconds on the zero-time move-out section.

A total of approximately 5500 seismograms were used to build the zero-time move-out section and a coherent reflected event at around 0 seconds was indeed identified and picked. A dataset made up of approximately 1250 picks, opportunely corrected, was used for the further step of the interface parameter inversion.

Five inversion runs were performed to obtain the final interface model using the reflected travel times and waveform semblance data recursively, as described in Vassallo and Zollo (2008).
The multi-scale approach was used in the inversion strategy so that models described by 2, 3, 5, 9, 17 parameters could be checked.

Moreover, when the reflector was defined by a small number of parameters (2, 3 and 5 nodes) the cost function based on traveltime residuals was used in order to find the best-fit model. Figure 8 shows the depth interval used in the search for the maximum likelihood model in the range of 1000 and 700 metres, using 2, 3 and 5-nodes to describe the reflector. These ranges were chosen according to the reflection time

**Figure 8** (a) Interface models retrieved by waveform inversions of reflected time picks. From the top to the bottom, interfaces with increasing number of nodes are shown. Black points represent the control points. Bars represent the interval range used. Points on the topography represent the source-receiver pair. (b) Residuals and histogram computed for the 5-node interface.
residuals obtained for each interface and assuming an average velocity of 4.5 km/s above the interface.

The inversion of reflection travel times for a 5-node interface model provided a RMS time residual of 0.05 s, comparable with the estimated error on arrival time reading for the modelled reflection event (uncertainties ranging from 0.04 to 0.07 s). With the aim of increasing the interface model resolution by using the waveform semblance data, a number of inversion runs was performed using a larger number of parameters (9 and 17 nodes) and waveform semblance data (Fig. 9).

The waveform semblance function, as defined in Vassallo and Zollo (2008), was computed for a time window of 0.2 seconds, centred at the theoretical travel times of the reflected phase.

The depth range used to perform the 9-node inversion was assumed equal to 500 m, based on reflection time residuals for the 5-node interface model and the same average velocity as above. Instead, the depth ranges for searching the new model (defined by 17 parameters) were chosen based on the errors computed for the 9-node interface model. Therefore, smaller depth ranges were considered for interface parameters associated with smaller errors.

Figure 8(b) shows the arrival time residuals computed for the retrieved 5-node interface. In the 7–16 km distance range, reflection points are very dense and associated with small reflection time residuals (±0.1 s) centred at 0 seconds, as shown also by the histogram.

Figures 9(a) and (b) (panels) show the interface models retrieved using 9 and 17 nodes, respectively. The two models differ essentially in the 8–10 km and the 14–17 km distance ranges, where the 17-node interface is deeper than the 9-node interface. As expected, as the number of nodes increases, the retrieved interface morphology appears more irregular.

Uncertainty estimation on interface depth

In order to estimate the uncertainty on node depths for the retrieved interface, a local exploration of the semblance function was performed. This procedure consists in computing the semblance values around the best fit model. The variation of
the semblance value for each node was computed varying its vertical position within a depth range of ±1000 m with a sampling interval of 50 m by maintaining the depth of other nodes fixed at their final best value (semblance plot). The uncertainties on node depths were estimated based on semblance plots by using the method described in Vassallo and Zollo (2008).

This procedure requires the definition of a minimum semblance level, which was estimated as follows. Starting from the whole available records, 200 sets of 3969 waveform signal windows (0.2 seconds wide) were randomly extracted and the semblance values were computed for each dataset. Hence, we assume that the random combination of waveforms extracted from the whole data section should provide the expected minimum semblance value. Figure 10 shows the distribution of the obtained semblance values with a Gaussian-like shape and an average value of 0.001. This value was used as a lower bound for the uncertainty analysis based on semblance plots (dashed line in Fig. 11). Figure 11 shows two examples of semblance plots for well and poorly constrained nodes. In both plots the maximum of semblance values was obtained relative to the best fit node depth (central value), while the two graphics differ for the function shape. A larger uncertainty is associated with a wider shape of the semblance function. Error bars in Fig. 9 are plotted for both the interfaces retrieved. Generally, the 17-node model presents larger errors than the 9-node model (497 and 381 metres respectively).

The corrected Akaike information criterion (Akaike 1974; Hurvich et al. 1989) was used to evaluate whether the data fit provided by the 17-node model was statistically significant relative to the 9-node model. Values of 96 and 175 were retrieved for models described by 9 and 17 parameters respectively and therefore the 9-node model was chosen according to the corrected Akaike information criterion.

Final zero-time move-out section

Using the discovered interface model, a zero-time move-out section was built, showing a phase alignment of around 0 s, where a maximum of the semblance value is observed (Fig. 12).

Figure 12 also shows that other phases appear at different two way times. In particular at −0.5 seconds an early reflection event is evident between traces 4300 and 4600 corresponding to an offset of approximately 13 km. This phase (pointed out by the arrows) also presents a pick in the semblance panel. Using an average velocity value of 4.5 km/s, a depth of approximately 1 km below the topography was estimated for this shallow reflector, whose depth matches well with the depth at which a sharp P-velocity change occurs on the retrieved tomographic model (Fig. 5).

DISCUSSION

The tomographic model obtained for the Val d’Agri area shows an abrupt ascent of the 5.2 km/s iso-velocity contour at a distance of approximately 11 km along the analysed profile. This ascent brings the depth of the 2.5 km/s iso-velocity contour from approximately 2 km to sea level. A fixed geometry test was performed to ensure that this feature was a reliable trend in the velocity field. The retrieved model is in good agreement with the tomographic model obtained by Dell’Aversana et al. (2003), which was constrained to match velocity values from log data.

P-velocities of 5.0–6.0 km/s are associated with carbonatic deposits while P-velocities of approximately 3.5 km/s are consistent with Plio-Pleistocene deposits outcropping in the basin zone (4–10 km along the profile, Fig. 1) as also suggested by Improta et al. (2002) and Dell’Aversana et al. (2003).

The inversion of waveform semblance from reflection data provides an interface model in the range of 2 to 3 km, deepening in the NE part of the profile. This interface morphology
matches well the trend of the 5.2 km/s iso-velocity contour in the tomographic model up to approximately 11 km along the profile. The interface morphology is also consistent in terms of deepening and depth, with a seismic discontinuity revealed by Dell’Aversana et al. (2003) based on reflection modelling and borehole data.

The reflected phase modelled in this work shows a relatively strong amplitude (Fig. 4) similar to that observed by Shiner, Beccaccini and Mazzoli (2004) by analysing a large number of seismic reflection data in this region. These authors suggest that the strong reflection event retrieved in the region is likely to be the marker of the top of the Apulian Carbonatic Platform, based also on several deep borehole data. According to the interpretation given by Dell’Aversana et al. (2003), we therefore suggest that the modelled P-to-P reflection event is associated with the top of the Apulian Platform. This hypothesis is also supported by structural interpretation performed by different authors for the Apulian Platform (Mostardini and Merlini 1986; Casero et al. 1991; Mazzotti et al. 2000; Menardi Noguera and Rea 2000; Dell’Aversana et al. 2002; Shiner et al. 2004 and bibliography therein).

A second reflection event, aligning at a smaller two-way time on the zero-time move-out section (Fig. 12) was detected by our analysis. The estimated event depth is approximately 1 km beneath the topography level, which is consistent with the ascent of the 5.2 km/s iso-velocity contour observed in the tomographic model.

Surface geology and well information allow us to associate this second reflection phase generated at cherty limestone deposits (Mazzoli, pers. comm.; Improta et al. 2000).

CONCLUSIONS

In this paper we tested a newly developed technique that permits the acquisition of reliable information on upper crustal structures in complex geological environments such as the Southern Apennines. This technique consists in a two-step procedure that combines tomographic and waveform semblance data inversion. The approach permits the retrieval of information on the investigated area in terms of velocity distribution and characteristics (geometry and depth) of the reflection events observed on seismic sections. The tomographic method is based on the computation of the \( a \) \textit{posteriori} pdf of model parameters (seismic velocity at grid nodes) using the Bayesian approach. Data are represented by first arrival traveltime picks and a maximum likelihood model is explored by using a non-linear optimization method and a multi-scale approach. The depth and morphology of seismic discontinuities embedded in a smooth background velocity model are also obtained by a two-step traveltime and waveform semblance data inversion with a non-linear optimization method and a multi-scale approach (Vassallo and Zollo 2008). The latter uses two different objective functions: the \( L_2 \) norm, based on the reflected traveltime picks and the semblance function based, instead, on the lateral waveform coherency. Both inversion methods include the topography in the inversion process, with the advantage of not considering in the computation any static corrections, as required for most standard migration techniques. This is particularly useful in complex geological environments with extremely irregular surface topography where the velocity variations, in proximity to the surface, often hamper the proper computation of the theoretical travel times required to perform static corrections.

The above methods have been applied to a global offset, industrial data set, acquired in the Southern Apennines by Enterprise Oil. We demonstrated that the joint use of different kinds of data gathering can help with the identification of reflection events in complex geological environments such as thrust belts.

A limitation regarding the waveform semblance data inversion procedure concerns the unmodelled complexity of both the velocity field and the interface geometry. In this case, indeed, different phases could occur in a small time interval, thus bringing errors into the phase identification by using the
semblance function even during the early stages of the inversion procedure. In these cases, the procedure cannot be totally independent of human intervention but rather a preliminary manual pick of the reflected phase is required.

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REFERENCES


Dell’Aversana P., Morandi S., Buia M. and Colombo D. 2002. Pre-stack depth migration of ‘Global Offset’ data integrated with high resolution magnetotelluric and gravity. 72nd SEG meeting, Salt Lake City, Utah, USA.


