Non-linear 2-D traveltime inversion in complex media: application to the Southern Apennines thrust belt (Italy).

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Summary

A new traveltime inversion method based on a non linear approach and multi scale process has been applied to a seismic data set acquired with a non conventional acquisition layout in a thrust-belt region. First arrivals and a main reflected phase have been hand picked. A first inversion is realized with only the first arrival traveltimes in order to obtain a 2D velocity image. The latter has been then used as background model for the interpretation of the reflected phase using another non linear multi scale inversion technique. Finally, the whole data set has been jointly inverted. The final velocity images are compared in order to assess the resolution and smearing effect. Moreover, the availability of a VSP survey allows us to independently assess the reliability of our results.

Introduction

In May 1997 an active seismic experiment was performed by Enterprise Oil Italiana S.p.A. on a test line in the Southern Apennines overthrust-belt (Italy). A high quality data set was acquired with a global offset acquisition configuration (Dell'Aversana et al., 2000) by deploying 160 receivers and 233 sources along a profile 14600 m long. The investigated area is characterized by a high structural complexity (i.e. strong vertical and lateral velocity variations) and presents a rugged topography. In such a context, seismic imaging of the crust by conventional reflection seismic is a difficult task.

Aimed at investigating whether complex shape reflectors and velocity structures can be properly imaged by non-linear traveltimes inversion, we used the global offset data set to test three new methods for the traveltime inversion of first-arrivals and reflected phases.

First, the information of the first-arrivals have been used to obtain an accurate 2-D P-velocity model by tomography. Then, we use the retrieved image as background velocity model for the traveltimes inversion of near-vertical/wide angle reflections in order to define the shape and the location of the corresponding interface. Finally, both the first- and the secondary arrival times are jointly inverted.

The comparison of the three images obtained with the different techniques allows us to discuss the problem of resolution and smearing effect when the target medium is very complicated. A VSP survey performed in a nearby well allows for the verification of the results.

Acquisition lay-out and arrival times picking

The seismic profile is 14400 m long and cross-cuts the main compressive structures in the investigated area. The topography along the profile is extremely rough: the maximum difference in altitude between sources reaching 700 m. A total number of 160 vertical geophones (90 m spaced) and 32 horizontal geophones (450 m spaced) were used. The sampling rate of seismic time series was 200 Hz. Sources had a move-up of 60 m and were produced by 4 to 20 kg of seismic gel housed in 30 m deep boreholes. The receivers recorded a total number of 233 shots.

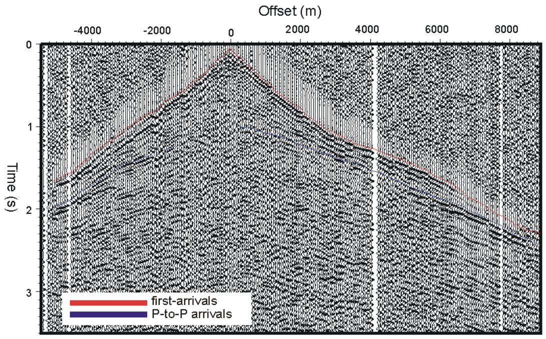

Figure 1: Representative Common Receiver Gather and examples of first- and P-to-P arrival time pickings. Note the large amplitude of the wide-angle reflections at offset larger than 4000 m.

First-arrival times have been picked on seismograms arranged in Common Receiver Gathers (CRG). A representative CRG vertical component section is displayed in the Figure 1. We followed a picking strategy based on the readings of a time window bracketing the presumed first-arrival time instead of a single reading with a weighting factor (Herrero et al., 2000). A total number of 6400 first arrival times have been accurately handpicked on 32 vertical component CRG sections. These sections have been selected based on the signal-to-noise ratio and on the receivers location along the profile, in order to ensure a homogeneous data coverage. The maximum offset for detecting first-arrivals ranges from 8000 to 13000 m.

We selected a main P-to-P reflected phase displaying large amplitudes on most of the CRG sections at offsets larger than 3000-5000 m (Figure 1). This phase is associated with arrival times of 0.8-1.5 s and normal move-out velocities of 3000-4400 m/s. Such a wide range of velocity suggests the presence of important lateral variations in the velocity field. The reflected phase has been picked both on CMP panels (nearly vertical reflections) and on CRG sections (wide angle reflections) after corrections for tomostatics and normal move-out. The data set consists of 1615 P-to-P arrivals.

First arrival traveltime inversion

The first arrival traveltimes are inverted by a innovative multi scale non-linear approach (Herrero et al., 2000). The forward problem is solved by using the fast estimator code of Podvin & Lecomte, 1991. Due to the very large number of model parameters the velocity model is parameterized by a regular and coarse grid of nodes. The velocity is assigned in each cell of the numerical grid by a 2D bi-cubic spline function.

The inverse problem is solved by searching the minimum of an objective function with a combination of global (Montecarlo) and local search (Downhill Simplex). Since it is rather impractical to retrieve by a single inversion run both the low and the high frequency contents of the velocity model, the inversion code uses a multi scale approach (Herrero et al., 2000).

The inversion technique described above has been applied to the first-arrival traveltime data set. The model reaches a total length of 16000 m and extends from the topographic surface to 2800 m below the sea level (hereafter b.s.l.). We used an absolute constraint consisting in a constant velocity band limit (100<Vp<6500 m/s) for all the parameters in order to avoid unrealistic velocities in the shallow crust. A checkerboard test has been applied to the final velocity model in order to assess the resolution. The best resolved region of the velocity model extends from the surface to about 1000-1500 m b.s.l. in the 4000-11000 m distance range.

The final model (Figure 2) displays a very complex velocity field with significant lateral and vertical velocity variations, both in the shallow and in the deep part. In the central part of the investigated section a high velocity (Vp=5000-5200 m/s) region is broken off by a vertical velocity inversion placed at about 700 m b.s.l.. At greater depth (1500-2000 m b.s.l.), we observe a sudden increase of the velocities from 5000-5500 m/s up to 6000 m/s. This velocity increase can be related to a strong seismic discontinuity which generates head waves observed as weak first-arrivals on CRG sections at offsets larger than 6000-7000 m (Figure 1). The presence of this interface is proved by the P-to-P traveltime inversion (see the next sections).

P-to-P traveltime inversion with a background velocity model

We use an accurate and fast technique to compute the reflection traveltimes for a given source-receiver couple based on two steps. The first step is the computation of the one-way traveltime from each sources and receivers to the uniformly spaced nodes of a medium grid by a finite-difference solution of the eikonal equation. These traveltimes are computed in the tomographic model. The second step is the search of the reflection point on a given interface for each source-receiver couple using the Fermat principle.

The interface shape is described by a implicit bicubic spline interpolation between nodes. The latter are retrieved with the same technique used for the first-arrival traveltime tomography. The minimum of an objective function is searched by a global-local coupled algorithm (Montecarlo+Simplex). The strategy adopted for the model space investigation is based on a progressive increase of the number of the interface nodes.

The inversion method has been applied to 1615 P-to-P arrival times (Figure 3). The resolution is assessed with a local exploration of the objective function around the final model. The retrieved interface is well resolved in the central region of the model where the background velocity model is trustable and the ray coverage is dense. Conversely, the interface is poorly resolved on the model borders where it is only sampled by near vertical reflections.

Aimed at increasing the accuracy of both the velocity image and the reflector, first- and P-to-P arrival traveltimes have been jointly inverted.

Joint inversion

The joint inversion technique combines the two methods previously described, which are very similar except for the parameterization. The velocity medium is separated in two media, one for the velocity above the interface and another for the velocity beneath it. Each medium is parameterized by a coarse grid of nodes, used for the bicubic interpolation. The grid expands on the whole model, the position of the interface being unknown a priori. In addition to the parameters of the velocity model, the nodes of the bicubic spline function which decribes the interface have to be taken into account.

The inverse method is based on a multi scale approach. It is applied to the whole data set (6400 first arrivals and 1650 P-to-P reflections). The final image (Figure 4) is similar at shallow depth to the image obtained only with the first arrivals. The main difference is close to the interface where the introduction of a sharp interface in the parameterization of the medium reduces the effect of the smearing.

Comparison with the VSP survey

A VSP survey has been performed in an exploration well located along the seismic line. In the figure 5 we compare the velocity model resulting from the VSP, the vertical velocity profiles extracted from the images of figures 2 and 4, as well as the depth of the interface retrieved by the second inversion.

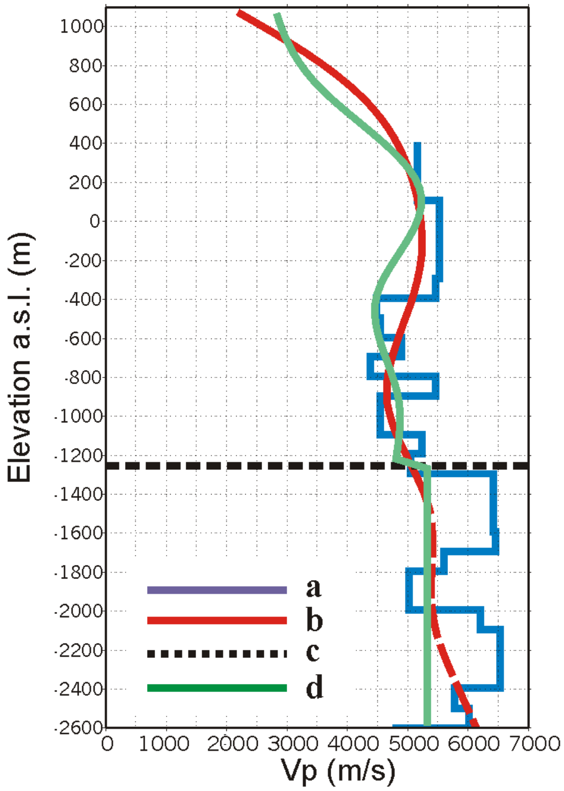

Figure 5: Comparison of the retrieved images with a VSP survey. a) Vertical P-velocity model determined by the VSP survey (the well location is indicated in figures 2, 3 and 4), b) 1-D P-velocity model extracted from the image obtained by traveltime inversion of first-arrivals, c) Depth of the interface retrieved by P-to-P traveltime inversion, d) 1-D P-velocity model extracted from the image obtained by the joint traveltime inversion of first- and P-to-P arrivals.

The VSP shows a high velocities (5200-5500 m/s) down to 400 m b.s.l., followed by a velocity inversion. The well penetrates the top of a high velocity layer (6500 m/s) at 1250 m b.s.l.. Although the velocity profile extracted from the tomographic model is smooth because of the bicubic parameterization, it is in agreement with the trend of the VSP. Moreover, well data fully confirm the result of the P-to-P traveltime inversion, the depth difference between the retrieved reflector and the top of the high velocity layer being about 30 m. The joint inversion confirms the previous results, with major details on the velocity structure above the interface.

In both inversions, the velocity under the interface is underestimated. This is not due to a misplacement of the interface as inferred by well data. As the lower part of medium is mainly sampled horizontally, errors on the model borders may influence the velocity under the interface. However, we must point out that the velocity values obtained by the VSP below the interface seems very high if compared with the corresponding lithology (cherths and cherty dolomites).

Discussion/Conclusions

We have developed three new methods for the non-linear traveltime inversion of first arrivals and reflected phases collected with a global offset acquisition configuration. The methods are specially designed to image very complex structures.

The application to the global offset data set acquired in the Southern Apennines (Italy) reveals the advantages of using the proposed procedures in overthrust-belt regions, where the source/receiver spacing is frequently irregular, the topography is rough and strong lateral velocity variations are present.

We combine the information carried by nearly vertical reflections and by first arrivals (the former sampling the medium vertically, the latter having predominant horizontal paths) in order to accurately image the velocity structure. Moreover, we take advantage of the wide-angle reflections which provide useful constraints on the dip of the reflectors.

References

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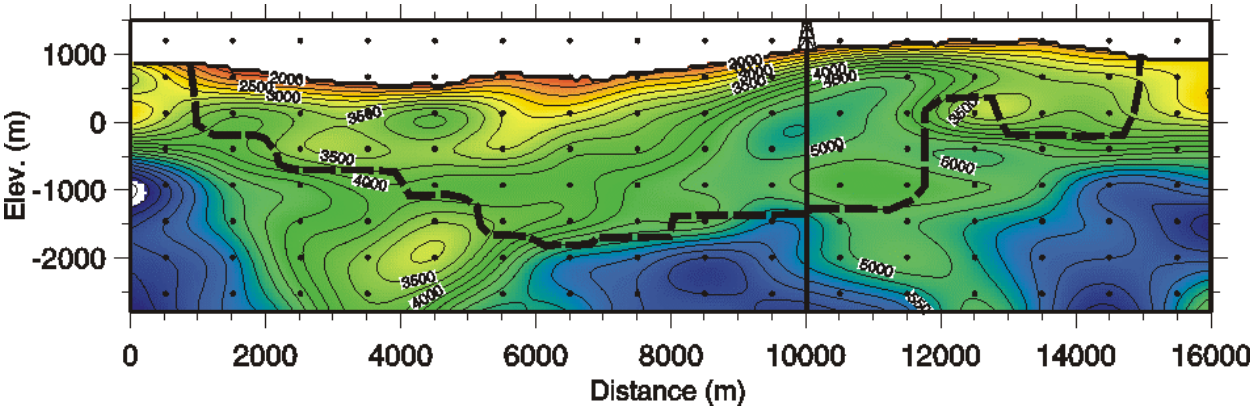

Figure 2: 2-D P-velocity model obtained by first-arrival traveltime inversion. The model parameters are depicted by black solid circles. The black dashed line bounds the best resolved region of the model. The well location is showed.

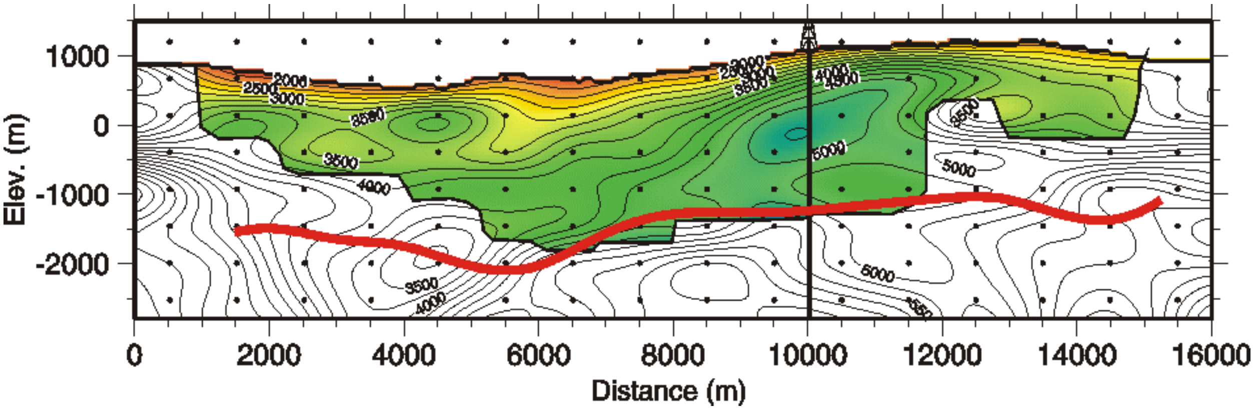

Figure 3: Interface obtained by P-to-P traveltime inversion of the selected reflected phase. The best resolved region of the background velocity model is plotted in color.

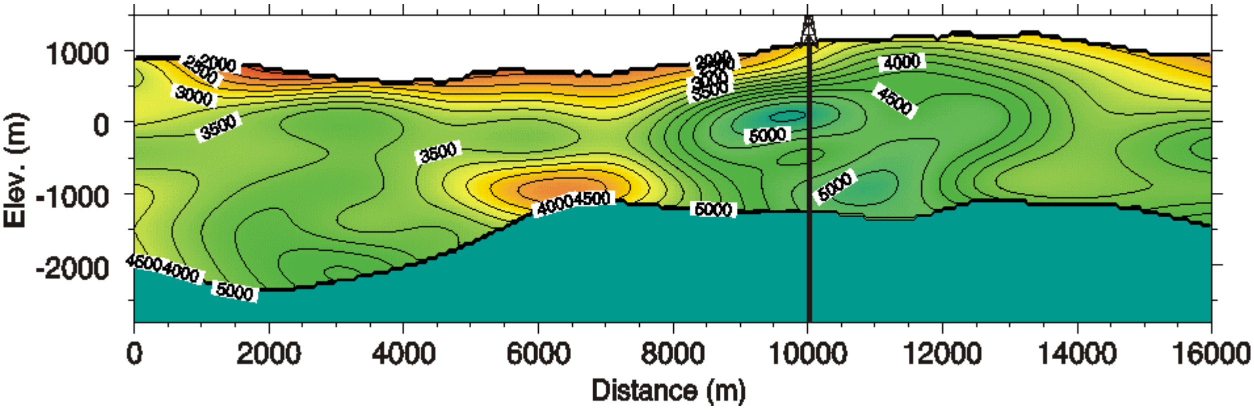

Figure 4: 2-D P-velocity model and interface obtained by joint inversion of first-arrival and P-to-P traveltimes.