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Tomographic depth seismic velocity model below the plain of Norcia (Italy) for site effect studies

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ABSTRACT This work represents a seismic investigation of the Norcia plain (Perugia, central Italy) for the characterization of the shallower structures for site effect studies. In particular, the aim of this analysis is to define the velocity model, down to 500-600 m below the topographic surface, and to identify the shape and depth of any reflective horizon and fault in the investigated area, with particular attention towards locating the boundary between bedrock and sedimentary cover. These features are of primary importance to evaluate the seismic response of the plain of Norcia. The tomographic inversion of the picked events, applied to this data set, allowed us to obtain a detailed depth model of the geological structures in correspondence of the acquired seismic lines.

Key words: reflection tomography, bedrock detection, velocity model, central Italy.

1. Introduction

The Norcia plain is one of the tectonic depressions of the central Apennines, characterized by high seismic hazard. Clear evidence of local site effects have been observed in the plain during the recent 1997-1998 Umbria-Marche seismic sequence (Bindi *et al*., 2004; Castro *et al*., 2004; Luzi *et al*., 2005) from the records available in the Italian strong motion database (ITACA, http://itaca.mi.ingv.it). Luzi *et al*. (2005) observed that the local site effects in this area can be ascribed both to the impedance contrast between the bedrock and the lacustrine sediments and to the diffraction of seismic waves at the basin border, which locally generate surface waves, observed as late arrivals in the seismic signals. In order to have sound bases to interpret any spectral analysis of seismic recordings and set up a geotechnical model of the plain, a detailed characterization of the basin geometry (i.e., sediment / bedrock interface) is necessary, together with the individuation of lateral and vertical velocity contrasts. For this reason a scientific cooperation between INGV (Istituto Nazionale di Geofisica e di Vulcanologia) and OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) was established. Two, multi-channel, seismic reflection surveys, for a total length of about 4 km, have been executed in order to define the velocity model down to 500-600 m below the topographic surface, as a first step of a more comprehensive study, which will involve seismic monitoring, geological and geotechnical investigations.

2. Geological and seismotectonic framework

The Norcia plain is one of the tectonic depressions located along the Norcia fault system. This system extends between Preci and Cittareale and is made up of four main fault sections, clearly visible as fault scarps in the carbonate mountain slopes bordering the intermontane depressions (Calamita *et al*., 1982, 1995; Brozzetti and Lavecchia, 1994; Galadini and Galli, 2000; Pizzi *et al*., 2002). Three sections of the system have been responsible for the formation – mainly during the Quaternary – of the Preci, Campi and Norcia basins (Galadini and Galli, 2000), while no basin formation is associated to the southernmost section of the system, detectable between Castel Santa Maria and Cittareale (Blumetti *et al*., 1990).

The Norcia basin, a sort of 10-km long, 3-km large rectangle in plan view, is larger than the other two basins and represents one of the typical (Plio?) Quaternary intermontane basins formed during the Apennine chain uplift (e.g., D'Agostino *et al*., 2001; Galadini *et al*., 2003). Similarly to other Apennine depressions, the tectonic evolution of the Norcia basin has been driven by the Quaternary activity of a main fault located along the mountain slope bordering the plain to the east. However, another fault, less visible from the geomorphological point of view, affects the western basin flank (Blumetti, 1995). Therefore, the Norcia basin has evolved as a half-graben in the first part of its tectonic history and progressively acquired the habit of a graben.

The recent (also Holocene) activity of the main fault is demonstrated by geomorphological and paleoseismological works done during the 1990s and in this century (e.g., Blumetti, 1995; Galadini and Galli, 2000; Galli *et al*., 2005). Fault motions can be attributed not only to the main fault located along the eastern mountain slope but also to minor sections very close to Norcia (Galli *et al*., 2005). In particular, the mentioned authors found paleoseismological evidence of at least two historical fault activations (possibly 99 B.C. and January 14, 1703).

The seismicity of the area is strictly related to the activity of the mentioned normal fault system (Galadini *et al*., 1999). In particular, the activation of the entire fault system resulted in the January 14, 1703 earthquake [M_w 6.7, *Is* X MCS at Norcia; Locati and Working Group DBMI (2009), from which all the macroseismic data reported in the following have been derived]. The other earthquakes, less strong than the 1703 one, were generated by the activation of the single sections of the system and occurred in 1328 (M_w 6.3, *Is* IX-X MCS at Norcia), 1730 (M_w 5.9, *Is* IX MCS at Norcia), 1859 (M_w 5.5, *Is* VIII-IX MCS at Norcia) and 1979 (M_w 5.8, *Is* VIII MCS at Norcia). Minor effects resulted from earthquakes not originated by the above mentioned fault system; in particular, Norcia suffered damage another 14 times between 1703 and 1997. The effects of the Umbria-Marche earthquake sequence in 1997 have been estimated with the degree VI of the MCS scale.

3. Data acquisition

The area selected for the investigations is located to the south of Norcia (Fig. 1). Two seismic lines were acquired in the area, with lengths of 3.4 and 0.7 km, respectively. The first line, located on a secondary road running south from Norcia, was designed following the best compromise between the purpose of the survey and the logistic problems due to seismic acquisition in an urbanized area; while the second line, perpendicular to the first one, was chosen to investigate the shape of the bedrock in relation to the presence of the central hill. Unfortunately, the morphology of the land did not allow us to extend this line on the hill,

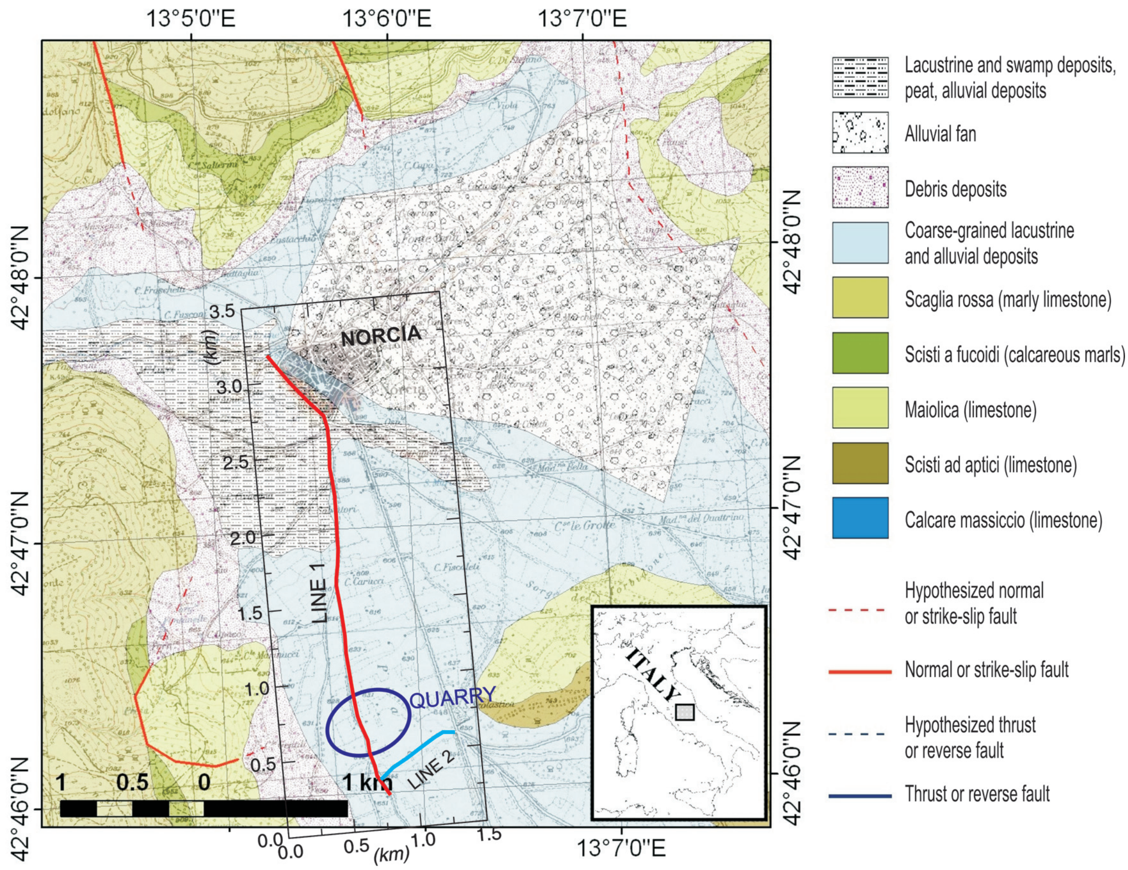

Fig. 1 - Geologic map of the Norcia plain and the acquisition area superimposed.

across the main road (Fig. 1).

The seismic source used was the IVI MiniVib system (Fig. 2a). For both lines, the distance between the receiving stations was 15 m, while the vibrates were shot at 30 m distance from each other. Each receiving station consisted of a group of 5 geophones aligned for a total length of about one meter (Fig. 2b); this geometry was chosen to reduce the random noise by stacking the traces of each station. Line 1 was characterized by 212 stations and 105 vibrates, while Line 2 by 52 stations and 27 vibrates. The values chosen for the sweep were: 10-250 Hz for the frequency range and 14 s for the sweep time. The energy of the vibrate was modified several times during the acquisition, using values from 2000 to 2800 pounds. For both lines, 3072 samples were recorded for each trace with a sampling interval of 1 ms.

The records immediately showed a significant degradation of data due to the presence of a low signal to noise ratio on both lines. The amplitude spectra for each trace of the vibrate 181 is shown in Fig. 3, to give an example of the recorded coherent noise along the line. The noise was mainly due to the presence of electric poles, car and truck traffic and noise from surface infrastructure (unfortunately, the lines pass near a gravel quarry with significant

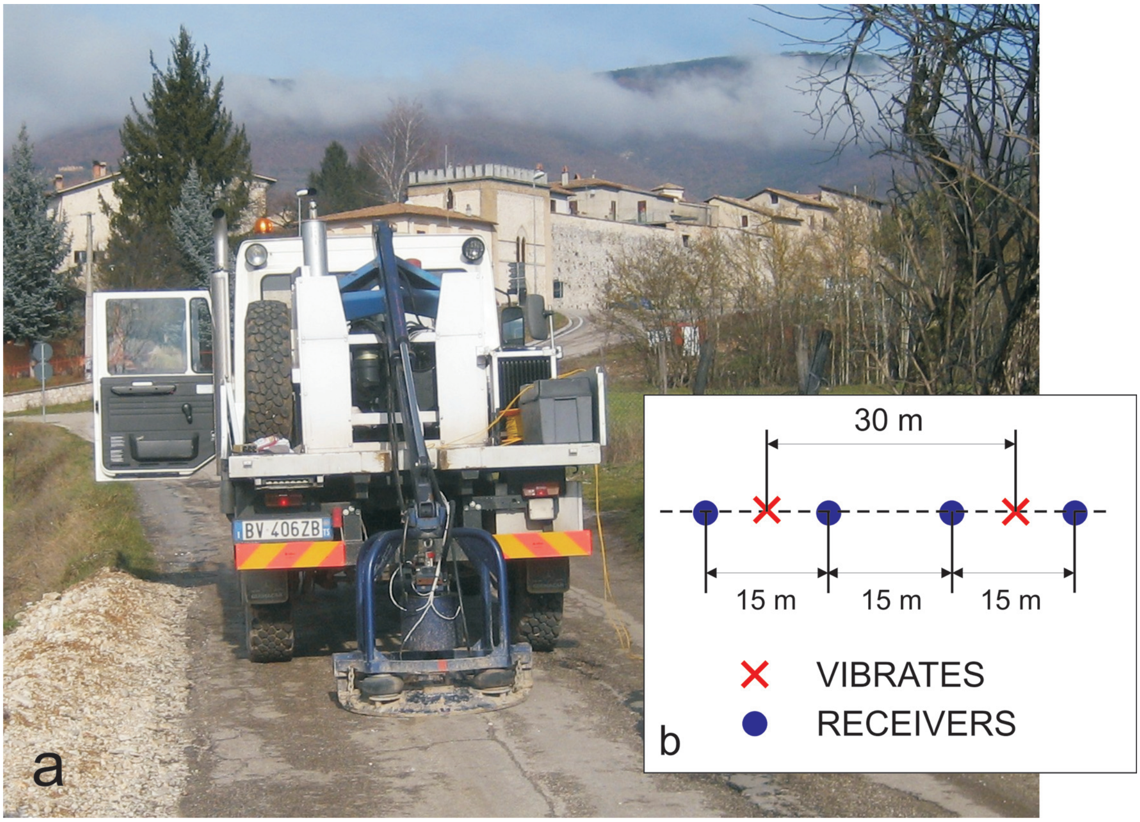

Fig. 2 - Data acquisition: a) IVI Minivib used as source; b) acquisition scheme.

activity during the day).

4. Data interpretation (picking)

Tomography is considered an efficient tool for estimating the seismic velocity in depth from the travel times of the waves propagating into the Earth. One of the most important aspects of the whole tomographic inversion procedure is related to the interpretation and extraction of the travel times from the data (picking). It is well-known that the quality of the inversion depends on the good quality of the original data. In our case, the excessive background noise and the low data quality required an accurate picking phase.

Three events have been identified, as shown in a common shot section of Line 1 in Fig. 4: the first one (red picks), associated with the early arrivals, corresponds to the typical pattern of diving waves (slightly divergent curves), which propagate in a medium characterized by a positive velocity gradient with depth; the second one (green picks), poorly defined, could be interpreted as a refracted signal (approximately straight picking line); the third one (yellow picks), more evident and characterized by a pseudo hyperbola, was related to waves reflected from a deeper horizon.

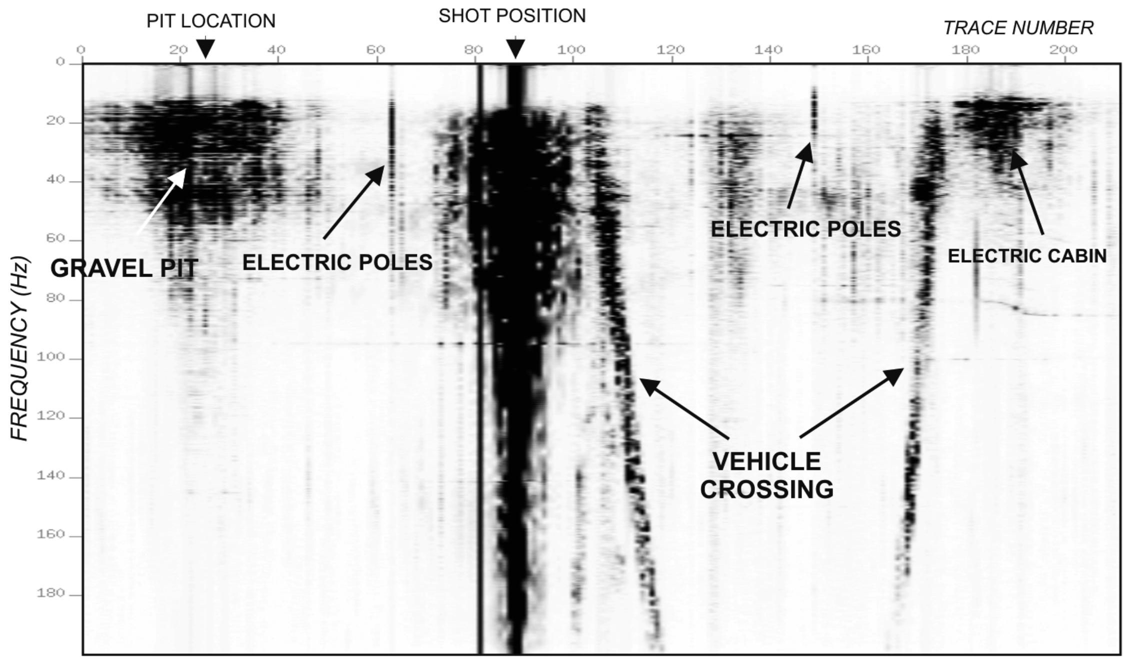

Fig. 3 - Amplitude spectra for all the traces of the vibrate 181.

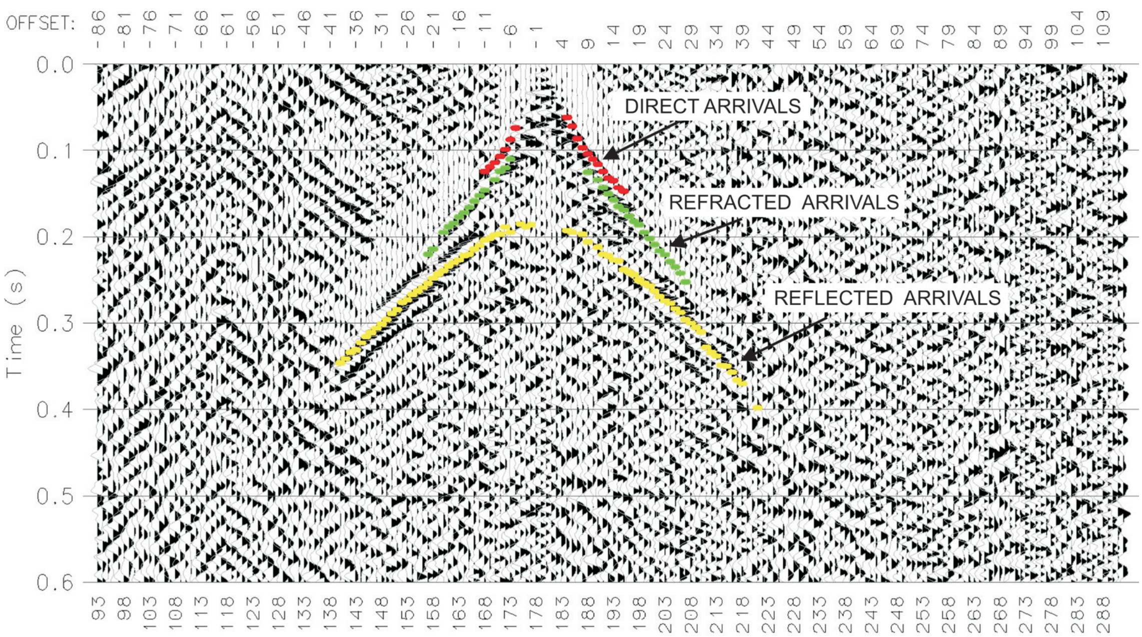

Fig. 4 - Picking of three different arrivals on common shot gather 179.

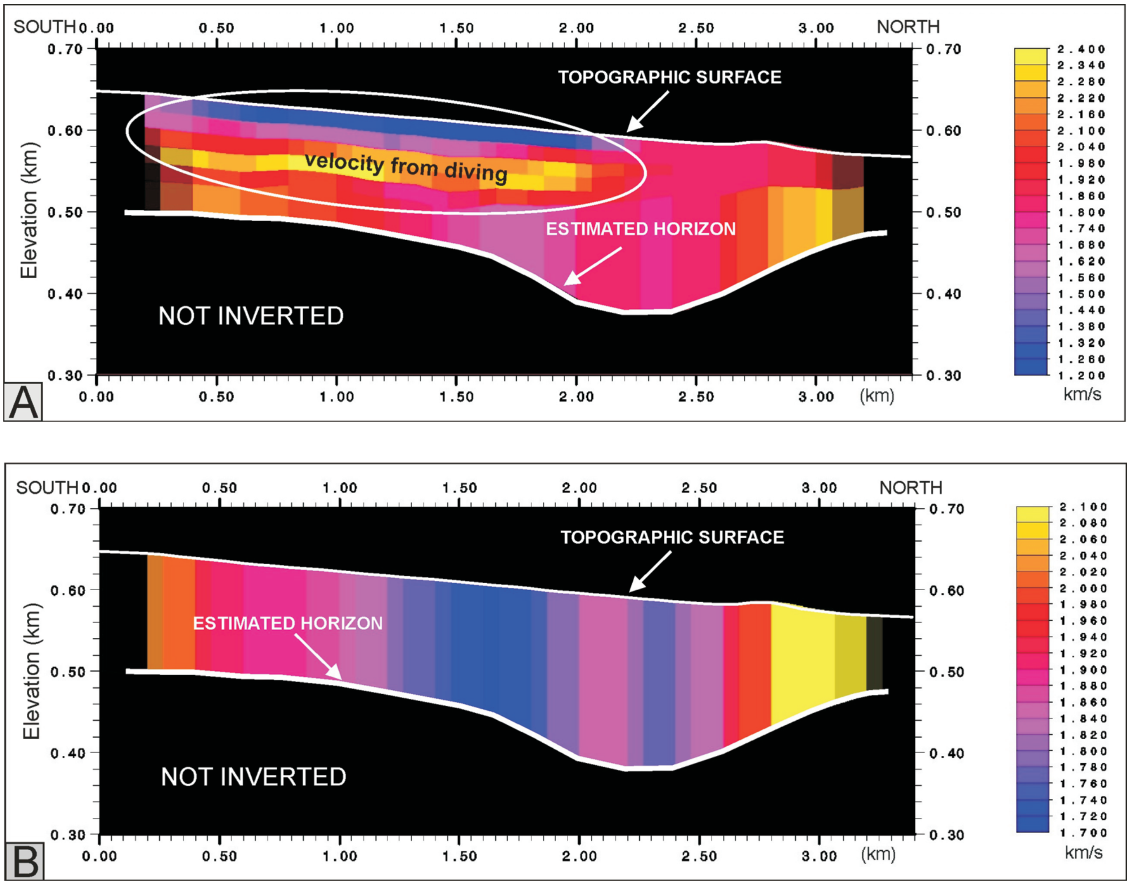

Fig. 5 - Line 1. Vertical section of the velocities obtained from the joint inversion of the direct and reflected arrivals (A) and from the reflected arrivals only (B). In black the zone not inverted.

Unlike Line 1, in the second line, only one strong reflected event has been recognized.

Some of the vibrates of Line 1 contain another horizon, but it was not considered in the inversion, it was present only along a small part of the line, less than ten shots.

5. Data inversion

The travel times inversion is an iterative procedure, where for each iteration the velocity field and, in presence of reflected events, the depth of the interfaces are upgraded. It starts from an initial guess, which can be a constant velocity model or derived from any a priori information (geology, well logs, etc.). In this analysis, we used the Cat3d software, a tomographic package developed at OGS, which utilizes a ray tracing method based on the principle of minimum time (Böhm *et al.*, 1999), the SIRT algorithm (Simultaneous Iterative Reconstruction Technique) to upgrade the velocities (Stewart, 1993) and the principle of minimum dispersion of reflection points to estimate the interfaces (Carrion *et al.*, 1993; Böhm and Rossi, 2004).

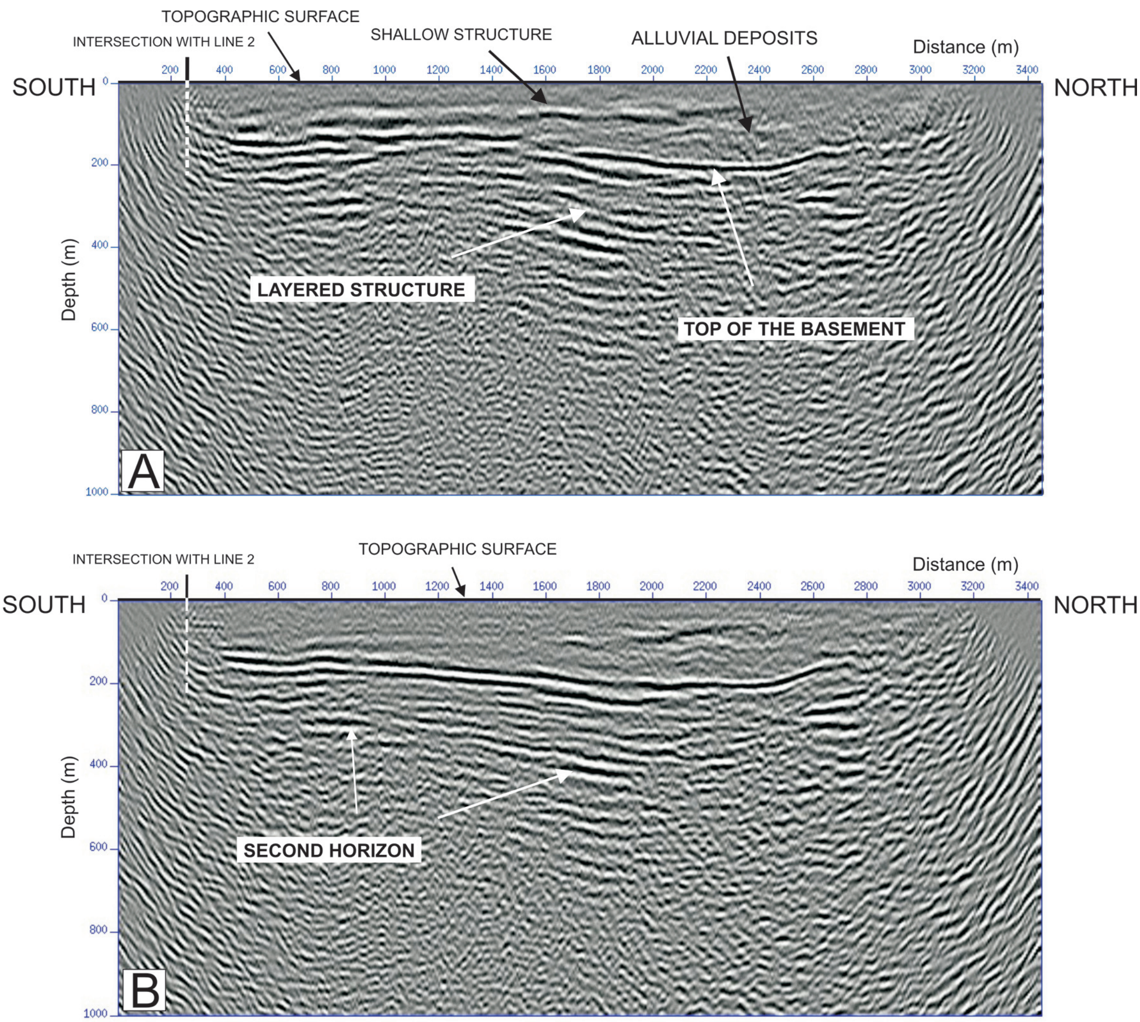

Fig. 6 - Line 1. Pre-stack depth migrated section by using the corresponding velocity fields of Fig. 5.

The tomographic inversion of Line 1 was performed using both direct arrivals, considered diving waves, and the first reflected event, associated to the horizon interpreted as the top of the basement. The use of different arrivals in the inversion, derived from the different raypaths associated with each wave type, increases the reliability of the inversion (Vesnaver *et al.*, 1999).

The joint inversion result is shown in Fig. 5a. This velocity field was then used to calculate the pre-stack depth migration by including the velocity value of 1.9 km/s (average velocity extrapolated from the deepest inverted layer) in the non-inverted part, below the picked reflections. The resulting seismic image is displayed in Fig. 6a, where a marked asymmetric warped structure of the sediments can be observed, characterized by a sequence of sub-parallel layers. Close to the top of the warped sequence, inside the alluvial sediments, a low frequency event is observed slightly leaning to the left (south), which may be associated to a high velocity

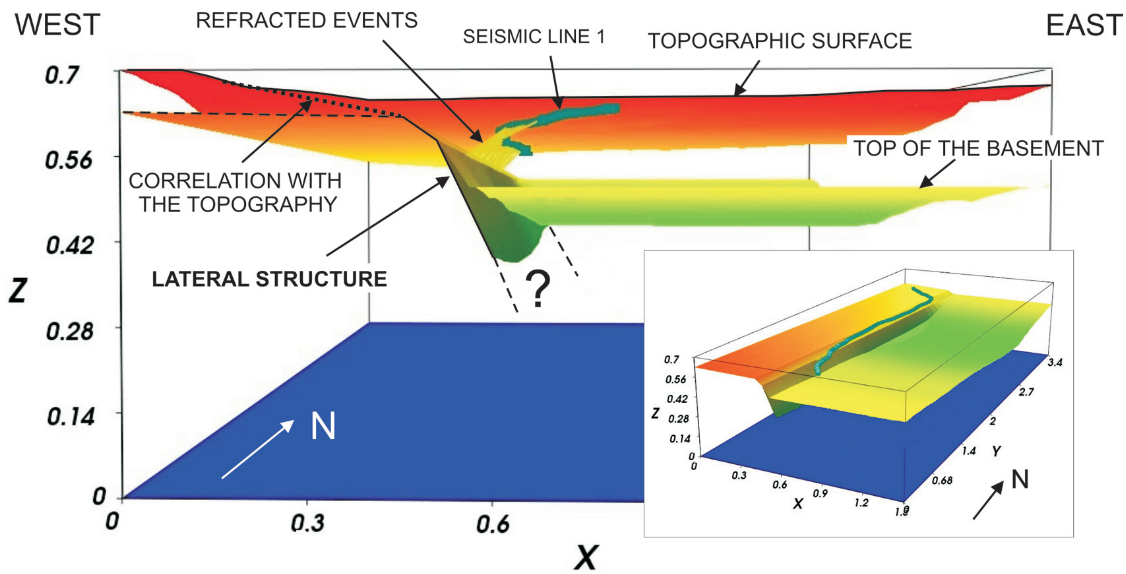

Fig. 7 - Intermediate model. The reconstructed refracted events by ray tracing (yellow lines) could justify the hypothesis of the presence of a lateral bending structure running parallel to Line 1.

anomaly at about 50-60 m below the topographic surface (yellow pixels in Fig. 5a). This high velocity zone is not easily explainable in shallow alluvial sediments and has no reasonable justifications. Moreover, if we observe the velocity field obtained by inverting only the first reflected arrivals (Fig. 5b), we observe instead the absence of high velocity values in the same area, although these values are hidden by the averaged velocity associated to the vertical pixels. This fact means that the anomaly is probably derived mainly from the diving arrivals. The corresponding migrated section (Fig. 6b) shows the attenuation of this shallower event, because of the absence of the high velocity zone.

A possible cause of this anomaly could be the presence of a lateral structure, bending towards the east and sub-parallel to the line, which might have caused the refracted events observed in the 2D section. In order to verify this hypothesis, we created a model containing a bending surface below the topography (as described in Fig. 7). The distance of this surface from the topography and the velocity associated to the lower layer was estimated by conventional refraction analysis (time intercept method) applied to the offset-time points of the refracted arrivals (green dots in Fig. 4). We computed the corresponding refracted arrivals on this lateral structure by using the same geometries of the real acquisition and compared them with the real refracted events to verify the consistency of this hypothesis. The results showed that this model could be a reasonable interpretation of those refracted events.

The second line was acquired in order to determine the trend of the bedrock near the outcrop in the centre of the plain (see Fig. 1, right of the quarry) and to verify a possible structural correlation with the outcrop itself. Unfortunately this line has the same signal degradation recorded on Line 1.

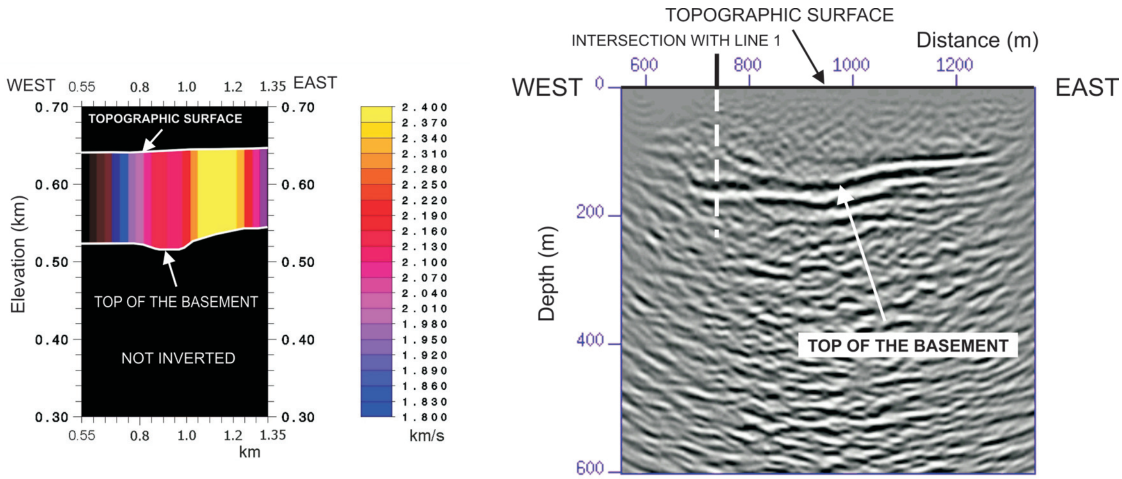

Fig. 8 - Line 2. Vertical section of the velocities obtained from the reflected arrivals (left). Prestack migrated section by using the velocity on the left (right).

The interpretation of Line 2, put in evidence only one strong reflected event, and no other clear events have been identified. The result of the tomographic inversion and the corresponding section of the migrated seismic data showed this event as a sub-horizontal reflector slightly leaning to the west (Fig. 8). This horizon is certainly associated to the top of the bedrock found in Line 1 (see the intersection points of Figs. 6 and 8); but its relative position and depth does not allow us to guess a possible direct correlation with the relief just to the east of the line (in the centre of the plan).

Unlike Line 1, no layered structures are observed on the seismic image of Line 2 below the top of the bedrock; probably due to the limited seismic spread used.

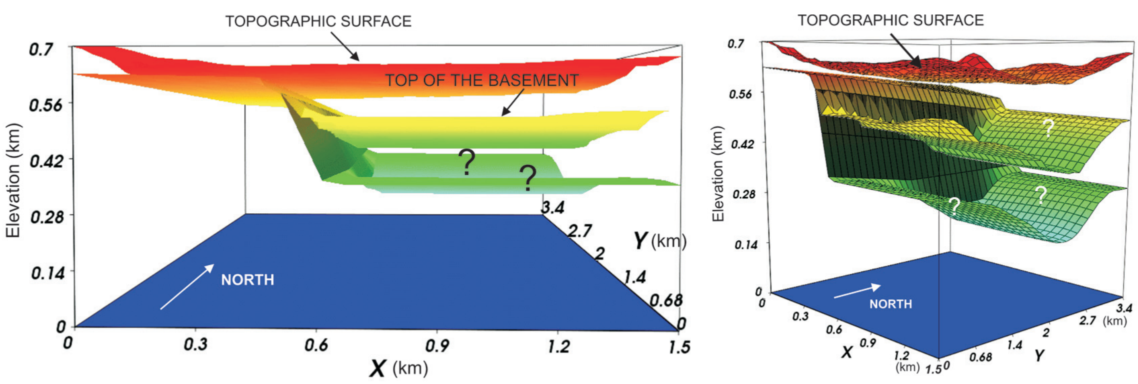

Fig. 9 - 3D image of the final model built by combining the two results obtained from the separate inversions of the two lines. On the right the model is squeezed in Y direction. The question marks correspond to the uncertain zones of the model.

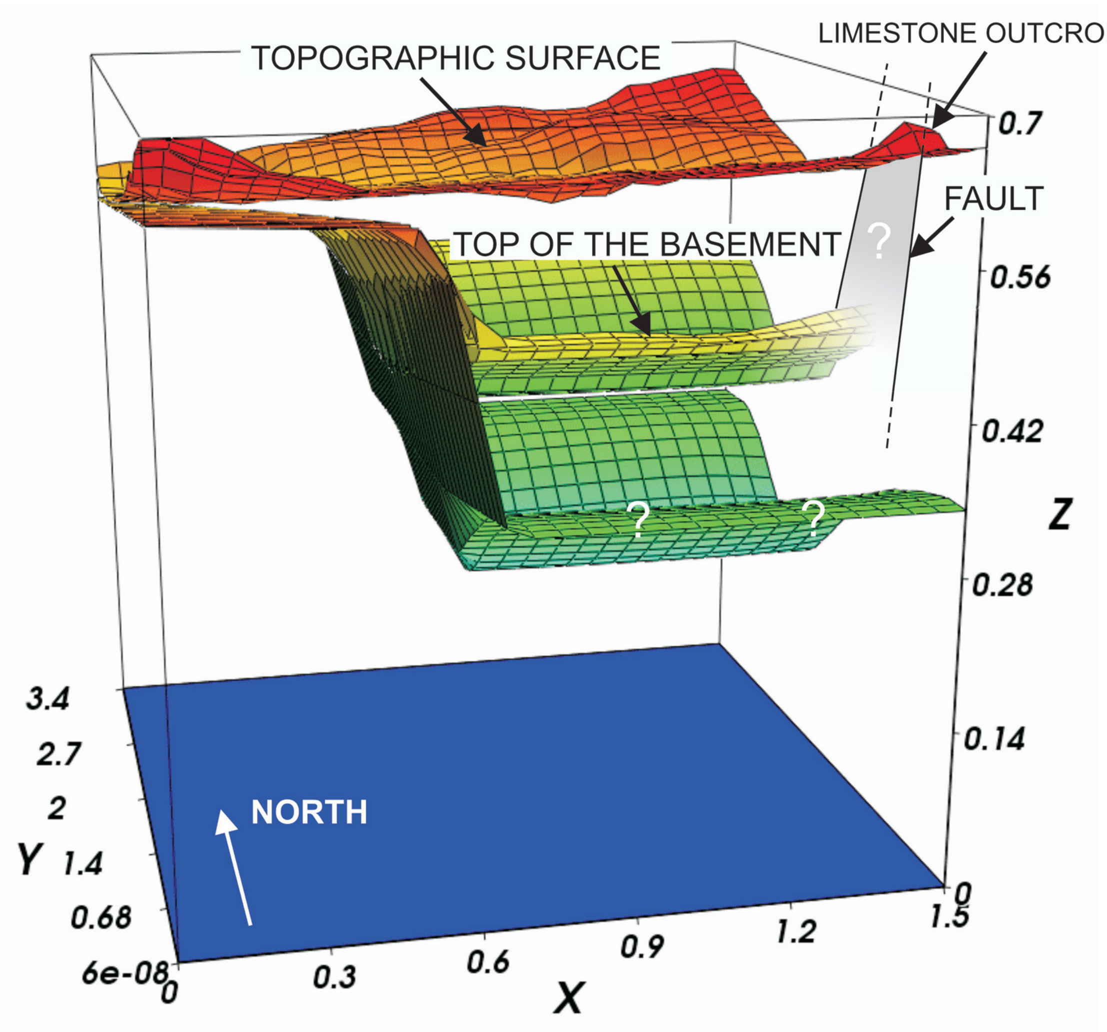

Fig. 10 - 3D view of the hypothesized correlation between the top of the basement and the limestone outcrop: note the presence of a direct fault on the right of the model.

6. The final model

Both lines are characterized by a well-marked horizon, the calcareous bedrock, below the alluvial deposits at depths ranging between 150 and 200 m from the topographic surface and characterized by an asymmetrically warped structure. This surface probably intersects the structure (normal fault?) leaning to the west.

The basement structure is layered, as shown in the seismic image of Line 1 (Fig. 6); in this figure another interface is identified as a strong reflection, at about 300-400 m in depth, which could indicate a marked lithologic change, although not visible in the seismic image of Line 2

(Fig. 8) probably due to the short size of the line. Moreover, in Fig. 8 the top of the bedrock does not appear to be directly correlated with the surface morphology immediately to the east of the line, as was hypothesized from the geological information before the seismic acquisition. Indeed, the relief east of Line 2, known as Poggio Valaccone, is carved into the carbonate bedrock (Fig. 1) and the fact that the top of the bedrock is quite deep in the seismic image is certainly surprising. The whole picture suggests that a fault may be present between the relief of Poggio Valaccone and the sector investigated by means of Line 2. The presence of faults within the inner part of the Norcia basin cannot be considered as anomalous. Indeed, as mentioned in the section dedicated to the geological framework, faults are also present in the area close to the historical centre of Norcia, east of the town, well within the basinal area (Galli *et al*., 2005).

The final model was defined by combining the two models obtained from the separate inversions of the two lines (Fig. 9). As the depth of horizons is reliable only in correspondence of the seismic lines, in the final model the basement has been extrapolated in the zones not covered by the acquisition, which correspond to the uncertain parts of the model (question marks in Fig. 9).

7. Conclusions

This work illustrates the results of a reflection tomographic experiment executed in the Norcia plain (central Italy) in order to define the velocity model, down to 500-600 m below the topographic surface, and to identify the shape and depth of any reflective horizons and faults of the investigated area.

By using tomography, the analysis provided a more accurate velocity model in depth with respect to the models obtained by standard seismic processing, From this model, some important results can be derived, if combined with acoustic facies interpretation and mapping, and used to calculate the local site effects in case of earthquake.

Two orthogonal lines were investigated and the tomographic results were merged to create a model of the depth position of the basement below the alluvial deposits.

The basement has a downward-shaped structure. In the western part of the area, due to the presence of lateral events in the seismic image, a fault system is hypothesized, directly correlated with the topography of the surrounding hills. Otherwise, the southern flank of the top of the basement does not seem to be directly correlated to the limestone outcrop present in the central part of the plain (Fig. 1); we can assume that a normal fault connects these two structures (Fig. 10). This hypothesis can be validated by the presence of a fault system in the north of the plain, which could be well correlated with this supposed fault (red lines in the upper part of Fig. 1).

The complete 3D reconstruction of the tectonic setting requires at least the acquisition of an additional line, perpendicular to Line 1 along the downward-shaped structure, in order to confirm the presence of the hypothesized western structure and define the eastward extension of the bedrock under the alluvial deposits.

To quantify the seismic site response of the plain, in the future, we plan to perform a more comprehensive study, including seismic monitoring and geological and geotechnical investigations.

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