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From 3D to 4D Passive Seismic Tomography - The Sub-surface Structure Imaging of the Val d Agri Region, Southern Italy

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SUMMARY

Local earthquakes (passive seismic) tomography (LET) is a well established tool for the imaging of the sub-surface structure. Alternative to active seismics, the main advantages of using natural sources are the better sounding in deeper portions of the upper crust, the relatively low cost, and the direct availability of S-waves. The main drawback is the achievable model resolution, which is limited by the density of the seismic network and the distribution of elastic sources, rather than the elastic wave frequency. Recently, 4D variations (in space and time) of velocity anomalies have been recognized in active volcanoes (Patanè et al., 2006) and normal faulting systems and ascribed to the medium response to transient geological processes, like dyke intrusions or fluid pressure increase on fault planes. In this paper we show how LET contributes to the imaging of the upper crust in a very attractive region like the Val d Agri in southern Italy, which hosts both significant oil fields and seismogenic structures. We show that LET allows to improve the definition of the crust structure, at depths larger than those sampled by conventional seismic profiles, and detect the space-time dependency of elastic properties in response to local variations of fluid pressure.

Data and Technique

The application of 3D and 4D LET is still limited by the availability of both data from local networks and automatic procedures able to robustly scan the massive continuous records to detect micro-earthquakes. In this paper we describe a very effective and accurate automatic analysis of a huge data set, a pre-requisite for such applications.

During May 2005-June2006, 23 seismic stations, equipped with both broad band and short period instruments, were operating in the Val d'Agri area, enclosing the main active normal faults (figure 1). The continuously recorded digital waveforms have been scanned with a fully automatic procedure that recognize the local earthquakes and furnish consistently weighted P-wave arrival times (Aldersons, 2004; Di Stefano et al., 2006). The local earthquakes identification is obtained via a *Sta/Lta* ratio based algorithm at individual stations. A minimum number of 4 stations was imposed to declare a trigger coincidence. The chosen settings were effective to detect very low magnitude earthquakes with a small number of false events. After event identification, the automatic picking procedure starts. The advantages of using an automatic procedure are the reduced time for the analysis, the highly accurate first-arrival *P*-wave picks, and the consistency in timing error assessment. The procedure requires a preliminary calibration with a reference dataset of very precisely human-picked data (in our case 700 waveforms from 120 seismic events). When the calibration is completed, the picker system is able to mimic the picking by a human analyst and give a consistent error assessment. The result of this automatic procedure is very successful, since most of the about 20000 P-phase automatic readings are comparable to those of a good human analyst. It allowed the preliminary location of about 4000 low-magnitude ($M_L > -0.2$) seismic events (Figure 1).

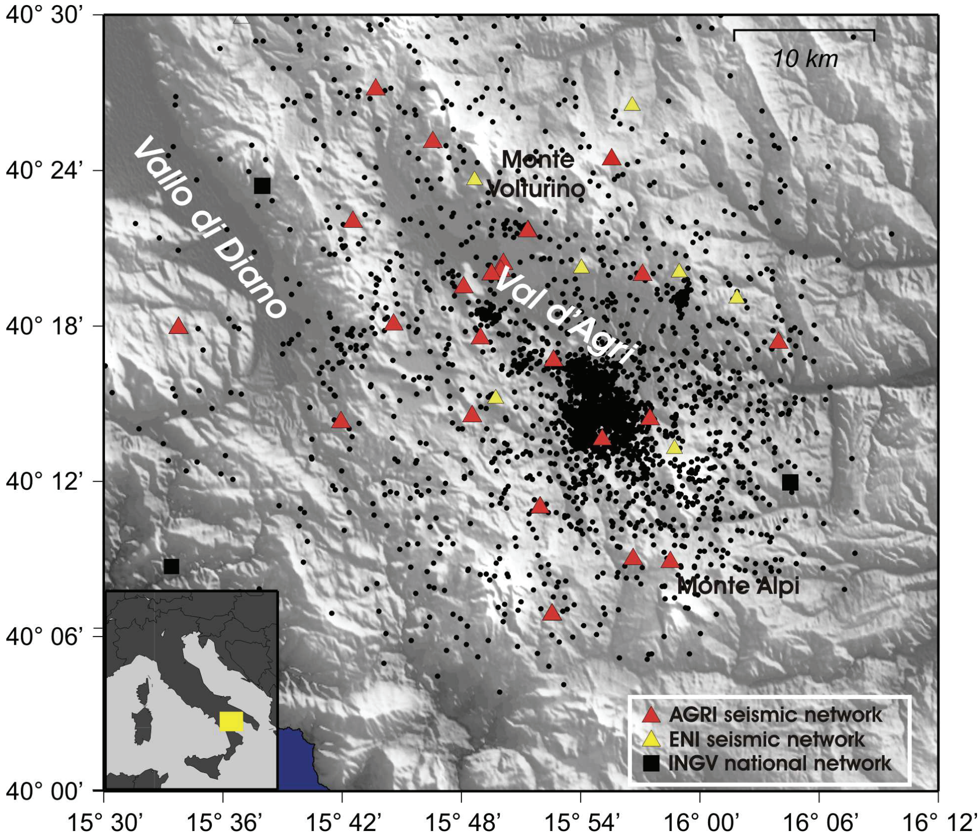

Figure 1: The Val d'Agri temporary seismic network (red triangles) complemented by permanent stations of the ENI (yellow triangles) and Italian National seismic network (black squares). Black dots represent the location of about 4000 low-magnitude ($-0.2<M_L<2.7$) seismic events recorded during the experiment.

From this dataset, we extracted about 700 events to verify the *P*-wave readings and to hand-pick *S*-wave arrival times. The implementation of the automatic S-wave picking is still in progress. For some of the selected earthquakes, the data set also includes arrival times from permanent stations of the INGV National Network and of the ENI network installed in the Lucanian Apennines. The selected earthquakes have location rms of residuals less than 1 s, location errors less than 1 and 2 km in the horizontal and vertical directions and more than 8 *P*-wave readings. In addiction, the selection optimizes the sampling of the target volume, avoiding the over-sampling of limited volumes.
For the 3D velocity model inversion, we use the linearized Simulps-13q (see Eberhart-Phillips and Reyners, 1997). We use 9269 P-wave and 8726 S-P arrival times from 667 local earthquakes, recorded at a maximum 50 stations. The model is parameterized by assigning a starting 1D velocity model, taken from the literature and a preliminary 1D inversion of the data, to a 3D grid composed by nodes spaced 3 km in the horizontal directions and six layers located at 0, 3, 6, 9, 12 and 15 km depth.
Previous tomographic studies in Italy have shown that the P-wave velocity in the Apennines upper crust is mostly influenced by lithology variation and the P-wave velocity ranges for rocks composing the upper crust are known (see Chiarabba and Amato, 2003; Improta and Corciulo, 2006, and reference therein). The structure is dominated by positive velocity anomalies mapping the location and geometry, although at a coarse scale, of the thrust rock units developed during the Mio-Pliocene compression. Shallow basins, related to the Quaternary extension, usually appear at the model surface layer as local low velocity anomalies.
Noticeable features of the 3D model are two large-scale WNW-trending antiformal structures characterized by Vp and Vp/Vs positive anomalies. We interpret these structures as structural highs of the Apulia Platform mainly consisting of highly fractured and fluid saturated limestones (figure 2).

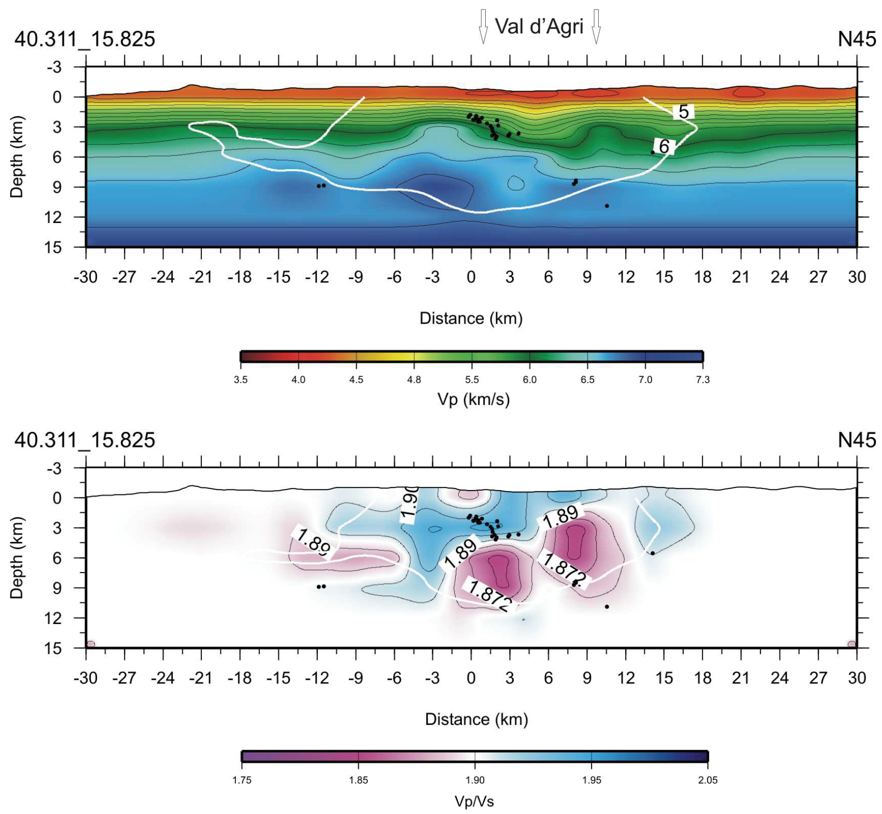

Figure 2: Vertical section of Vp (top) and Vp/Vs (bottom) across the Val d'Agri region. Micro-earthquakes are plotted as black dots, the white lines indicate the well resolved crustal volume.

This intepretation is also supported by the good match between the 6.0-6.2 km/s isovelocity contours and the top of the Apulia Platform (the target of oil exploration) mapped mainly by wells and MT data by Dell'Aversana (2003). Noteworthy, LET well defines the Apulia platform geometry beneath the Quaternary Agri basin, where commercial reflection profiling yields, instead, extremely poor-quality images of the target (Shiner et al., 2004).

From 3D to 4D

To investigate the presence of time variation of elastic parameters, we compute for each event the linear least squares regression of the S-P arrival times vs P-wave traveltimes (figure 3). The Vp/Vs computed for each event, are averaged through the time, using a moving overlapping window that encompasses 20 days and it is shifted of 10 days. For each time window, we compute the average Vp/Vs and the associated error weighting the Vp/Vs of the events with the inverse of their single standard deviation. After a first decrease of the Vp/Vs in the first 90 days, a rapid increment of the Vp/Vs is observed since day 240. This high value precedes a period characterized by an increased rate of seismicity (from day 300 to day 360). The largest seismicity production detected during the experiment is observed after the occurrence of the high Vp/Vs pick, when the Vp/Vs values rapidly fall into a background value of 1.92. These observations suggest the occurrence of 4D variations of elastic parameters in the region, probably related to fluid migration.

Conclusions

We have shown the strong improvement in the definition of the Val d'Agri structure and active processes in the upper crust achievable with LET. 3D models well image the regional trends of the Apulia platform beneath the Agri basin, in areas where reflection seismics provides poor-quality images. We find temporal variations of Vp/Vs which testify transient fluctuations of pore pressure on the fault system. This evidence supports the development of 4D tomography, but a re-processing of the data, which were not included in this 3D inversion, is needed to achieve a consistent time-resolution of 4D models. To optimize the performance of 4D tomography, we believe that the most important issue is the use of automatic analysis and procedures able to extract all the information contained in seismograms.

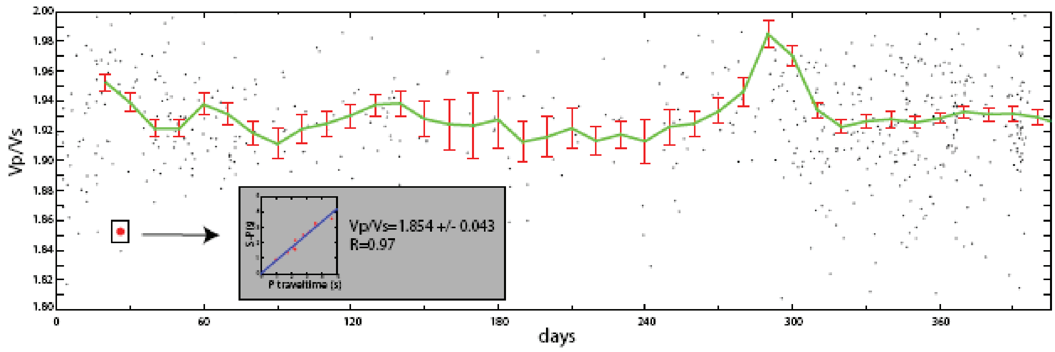

Figure 3: Time average Vp/Vs trend vs the time (green line). The time scale (days) begins when the temporary seismic array has been completely installed (reference time). For each event, the X value is the difference between the origin time and the reference time. The red bars indicate the uncertainties of the average Vp/Vs values inside each 20 days long moving windows. Black dots are the Vp/Vs for each events as obtained by the Wadati diagram.

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