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Integrated interpretation of seismic and resistivity images across the «Val d'Agri» graben (Italy)

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Abstract
Val d'Agri is a «recent SSW - NNE graben» located in the middle of the Southern Apennines thrust belt «chain» and emplaced in Plio-Pleistocene. The recent sedimentation of the valley represents a local critical geophysical problem. Several strong near surface velocity anomalies and scattering degrades seismic data in different ways and compromises the seismic visibility. In 1998, ENI and Enterprise, with the contribution of the European Community (ESIT R & D project – Enhance Seismic In Thrust Belt; EU Thermie fund) acquired two «experimental seismic and Resistivity lines» across the valley. The purpose of the project was to look for methods able to enhance seismic data quality and optimize the data processing flow for «thrust belt» areas. During the work, it was clear that some part of the seismic data processing flow could be used for the detailed geological interpretation of the near subsurface too. In fact, the integrated interpretation of the near surface tomography velocity/depth seismic section, built for enhancing the resolution of static corrections, with the HR resistivity profile, acquired for enhancing the seismic source coupling, allowed a quite detailed lithological interpretation of the main shallow velocity changes and the 2D reconstruction of the structural setting of the valley.

Key words *ESIT project – seismic imaging – tomo-statics – integrated interpretation*

1. Geological framework and geophysical context

«Val d' Agri» is located in the middle of the Southern Apennines thrust belt «chain» and in this context the «Val d'Agri graben» is a typical recent «tectonic valley» controlled by SSW and NNE dipping high angle Pleistocene faults.

This structural setting represents the Apennine maximum extension direction associated with the middle Pleistocene-Holocene normal tectonic regime, where the youngest tectonic elements are normal NW-SE trending faults with associated N-S trending left – lateral strike – slip faults, superposed onto the pre-existing Apennine fold and thrust structures (Hippolyte *et al.*, 1994a,b).

The sediments of the valley are essentially Plio-Quaternary marine, lacustrine and fluvial deposits of highly variable lithology and thickness (0 to several hundred meters). The youngest stratigraphic units of the valley are coarse to fine grained alluvial deposits and coarse slope «breccias».

Below the «valley» the Apennine thrust belt is characterised by «embricate» structures with extreme vertical and later tectonic displacements.

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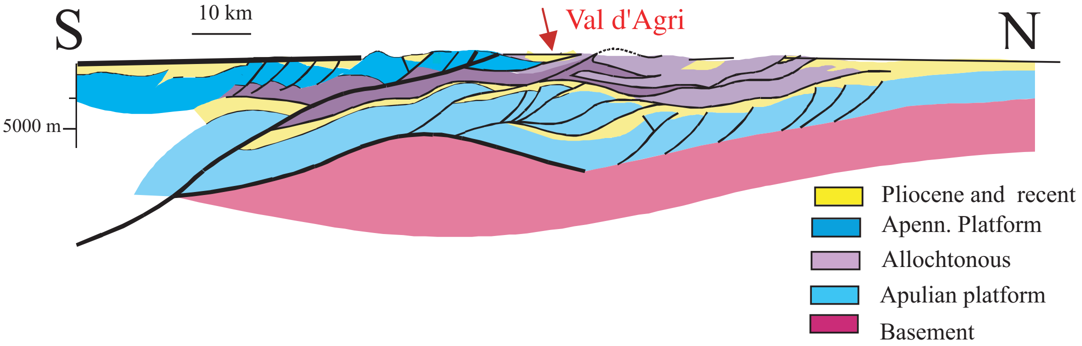


Fig. 1. Geological cross section across Southern Apennines.

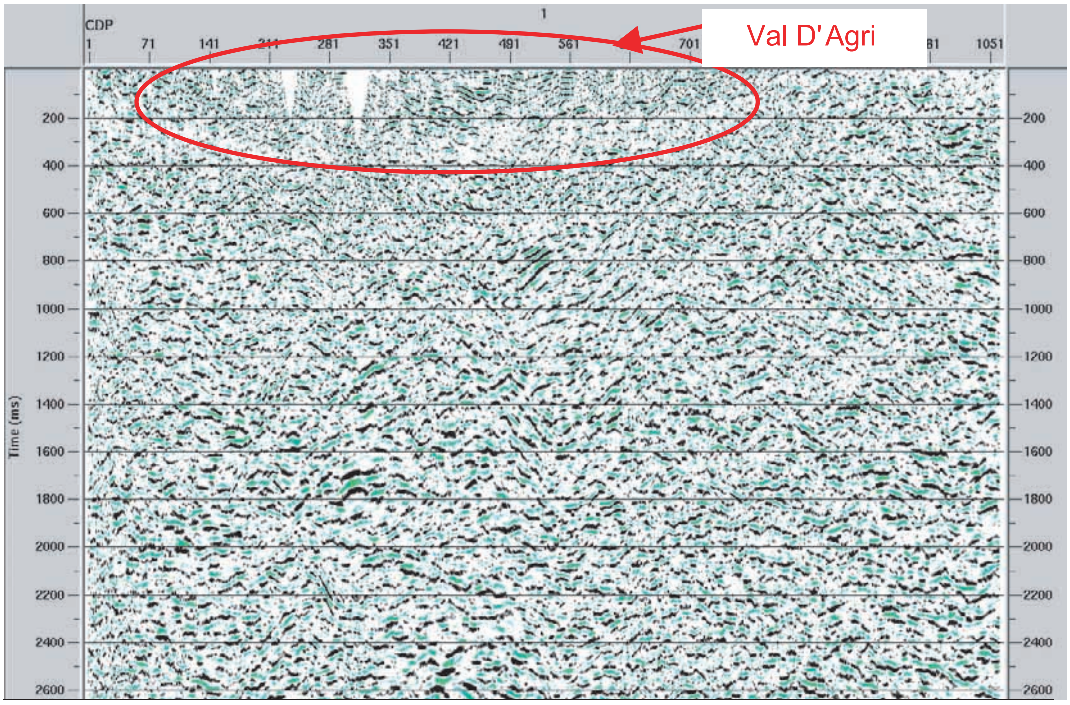


Fig. 2. Example of conventional seismic image across Val d'Agri.

In this context the sediments and the tectonic environment of the valley are a sort of recent and thin «roofing» above the Apennine complex geological setting (fig. 1).

This recent sedimentation is the cause of an important local geophysical problem. In fact, the presence of this recent sedimentation has a negative impact on seismic data quality and degrades the seismic image.

– Significant shallow velocity variations and anomalies.

– Heavy wave scattering noise that masks the seismic reflections.

And, in particular,

– serious problems for optimizing static corrections,

– very poor quality of the seismic image, are the usual geophysical consequence on seismic of this «thin roofing» above the «Apennine imbricate structures» (fig. 2).

2. 2D resistivity and seismic acquisition tests

Innovative methodologies have recently been tested in Val D'Agri for enhancing seismic visibility.

In late 1998, ENI and Enterprise, with the contribution of the European Community, acquired two experimental 2D seismic lines associated with two relative high resolution resistivity profiles across the valley (fig. 3).

The results obtained on *line A* (crossing Tramutola village, Monticello hill and Villa d'Agri village) are illustrated in this paper.

One of the purposes of the test performed was the analysis of methods able to improve seismic data quality by optimising acquisition source coupling and static correction efficiency.

The assumptions were that:

– The application of correct statics to the seismic data may improve the continuity of

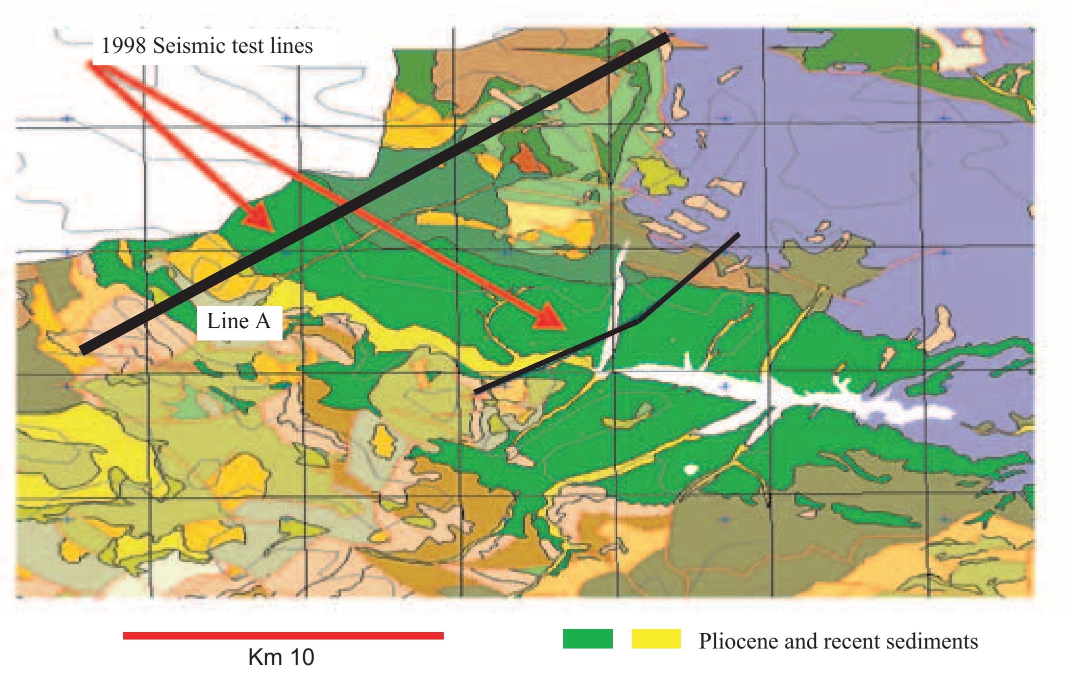


Fig. 3. Location of the 1998 2D seismic test lines.

events, produce a better subsurface image, and give a more appropriate relative position in time domain to each single reflection.

– The presence of an HR resistivity profile along the seismic line may aid the individuation of the shallowest «clay sequences» of the valley, that represent the optimal lithology for seismic source coupling during the acquisition of the seismic data.

2.1. *HR resistivity survey*

The equipment used for the HR resistivity survey and the recording parameters were the following:

– Equipment: AGI - STING R!; 256 Electrods; 1 to 599 mA; 320 to 800 V; reading cycle: 1.2 to 14.4 s.

– Recording parameters: AB/2 120 to 500 m; dipole length ranges: 5 to 12 m; max number of electrodes deployed at any one time: 56; no. of soundings along the seismic line: 15.

The interpretation flow was based on the 2D inversion of each single «automatic true resistivity section» and their «stack» along the line (fig. 4).

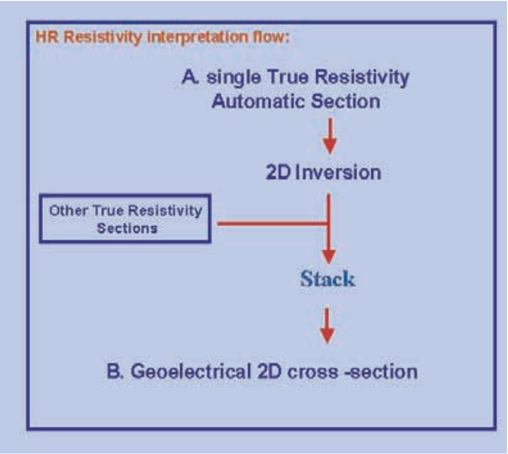


Fig. 4. HR resistivity section – interpretation flow.

2.2. *Seismic survey*

The seismic survey was acquired by the «Sercel 368 recording unit» using both together «conventional near vertical roll along» and «global offset» combined recording techniques (Dell'Aversana *et al.*, 1999, 2000). The seismic was recorded using offsets of 3000 to 18 000 m, max CMP fold of 12 000% and source depth and coupling variable; optimised following the HR resistivity data indications.

However, the near vertical seismic information was only used for tomostatics and near surface tomography processing.

The roll along 2D near vertical seismic recording parameters and layout are schematised in fig. 5.

3. Near surface seismic tomography processing

The roll along near vertical seismic shots have been only used for near surface tomography issues.

With the purpose to enhance the seismic static corrections resolution, «Statics» have been calculated by the near surface tomography approach based on the travel time inversion of the near vertical seismic first arrivals (Zhu *et al.*, 1992, 1998).

Tomographic inversion was based on analysis of the automatic and/or manual picking arrival time of the turning waves. This has been done on each SP along the entire near vertical offset (3600 m).

There are three distinct steps to perform the above process:

1) Divide the model into initial grid cells.

2) Ray trace through the model and compute source to receivers travel times.

3) Construct an inversion matrix from the ray-traced result and solve the linear equations.

The commercial «H. Russel GLI3D software» was used to perform the job.

The tomographic inversion method implemented within GLI3D uses a new approach that abandons rays and uses a wavefront method in both the forward and inverse processes.

This has two advantages: the first is a finite-difference algorithm for the rapid and accurate

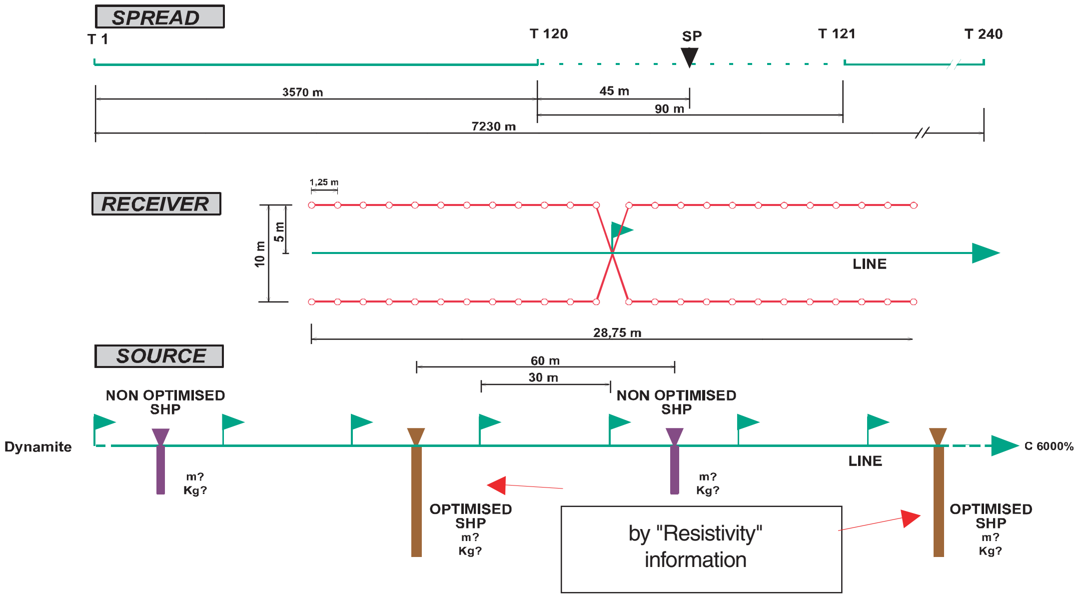


Fig. 5. Roll-along 2D near vertical seismic recording scheme.

forward modeling of travel times (previously done using ray tracing); the second is the application of a new much faster inversion procedure in order to calculate the back propagation of errors and thereby updating the velocity model (previously done by the solution of linear equations). The inversion process is initiated with an estimate of the true velocity structure (Hampson and Russell, 1984).

The first arrival time is computed by solving the eikonal equation, which calculates the first arrival time from a source location to each point within the model. The method is rapid and accurate, and properly handles the various wave types that comprise a first arrival (fig. 6a).

It can also be applied to a heterogeneous medium with moderate velocity variations. The errors between the observed and calculated travel times are then calculated and back propagated to the source and the model velocity is updated during the back propagation. The velocity updates are calculated by using a gradient search technique that minimizes the discrepancy between the observed and calculated travel times.

The back propagation algorithm is originally introduced in the field of computer neural networks as a training algorithm. It is a generalization of the least square algorithm.

It uses the gradient search technique to minimize the mean square difference between the desired and the actual network output.

The inversion is done shot by shot. The iteration «loop» is repeated until an acceptable match is obtained between the observed and calculated travel times (fig. 6b). There are two iterative techniques available in GLI3D: ART (Algebraic Reconstruction Technique) and SIRT (Simultaneous Iterative Reconstruction Technique). With ART the velocity model is updated for every shot following each iteration, and with SIRT the model is updated after all shot records have been modeled.

The inversion method implemented within the «HR GLI3D software» is calibrated based upon the pick time, such that the error between the observed pick time and the modeled pick time is minimized.

Eight iterations were executed during the seismic tomography processing. The iterative procedure was stopped when:

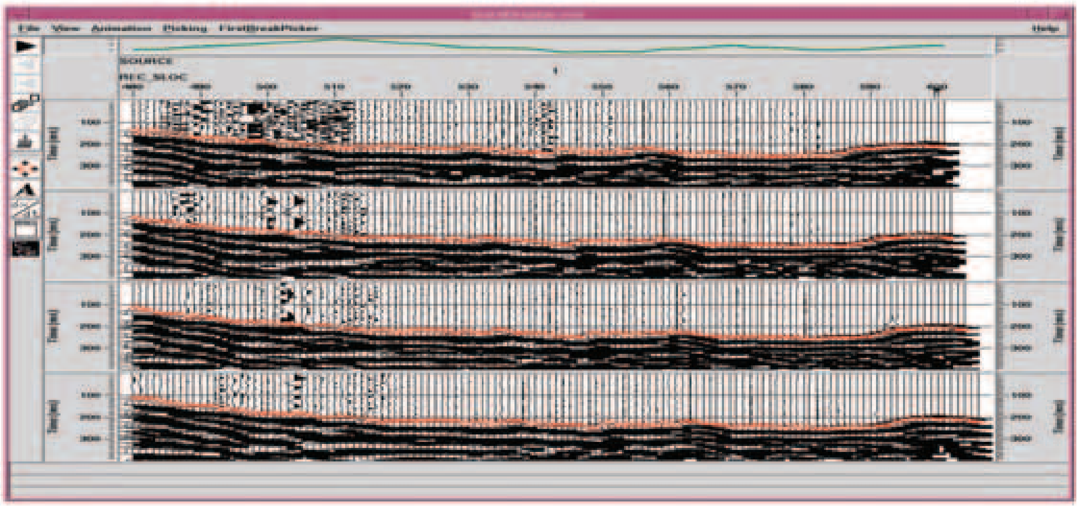


Fig. 6a. Automatic picking on LMO corrected shot gathers.

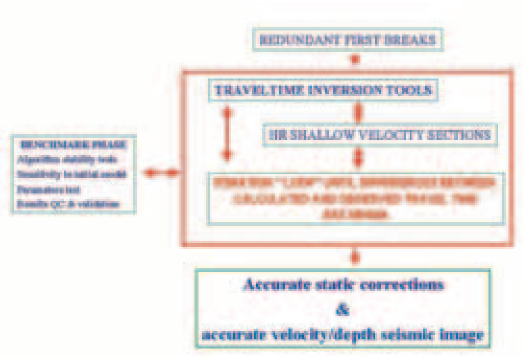


Fig. 6b. Near surface tomography processing flow.

– No substantial improvement or modification was obtained in the model by increasing the number of iterations.

– The differences between observed and calculated travel times were estimated as minima.

The resolution is maximum in the central area of the seismic section and reduces sensibly in function of spatial ray coverage and density. The ray coverage is redundant and constant along the entire section and it usefully investigates the first 400-500 m of the subsurface along the entire profile. The maximum investigation of the subsurface in the final velocity/depth model is around 800 m.

4. Imaging improvements

The near surface tomography results have been used in two different ways.

Tomostatics improved the static correction resolution and consequently the conventional seismic time image of the valley.

In fig. 7 conventional statics processing and near vertical tomostatics are compared. It is easy to note the improvement of the seismic image obtained using tomostatics relate to the conventional elevation statics based on the SP uphole time correction.

However, despite the sensible improvement, any detailed lithological and structural interpretation of valley is possible using this conventional TWT representation of the seismic information.

Near vertical tomography velocity/depth model showed surprising and significant details inside the valley.

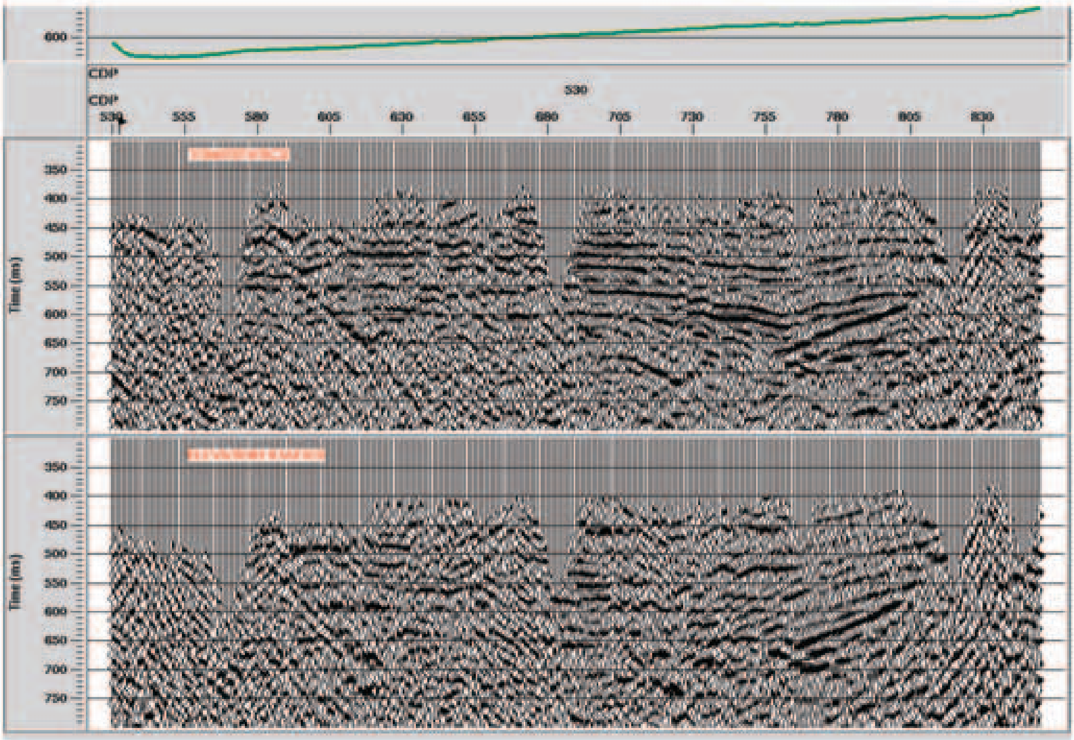


Fig. 7. Two Way Time (TWT) image of the Val d'Agri valley using tomostatics or elevation statics processing.

A new integrated interpretation as for the lithological than for the structural interpretation of the valley was possible using the near surface tomography representation of the seismic information.

In fact, the «high resolution shallow velocity/depth seismic model» displayed by the near surface tomography of the first arrival allowed at the same time (figs. 8 and 9):

– An unconventional representation of the shallower part of the seismic information.

– A significant illumination of the structural setting inside the «Val d'Agri graben» to 1000 m at least, as it was never done in the past by conventional seismic images (fig. 10).

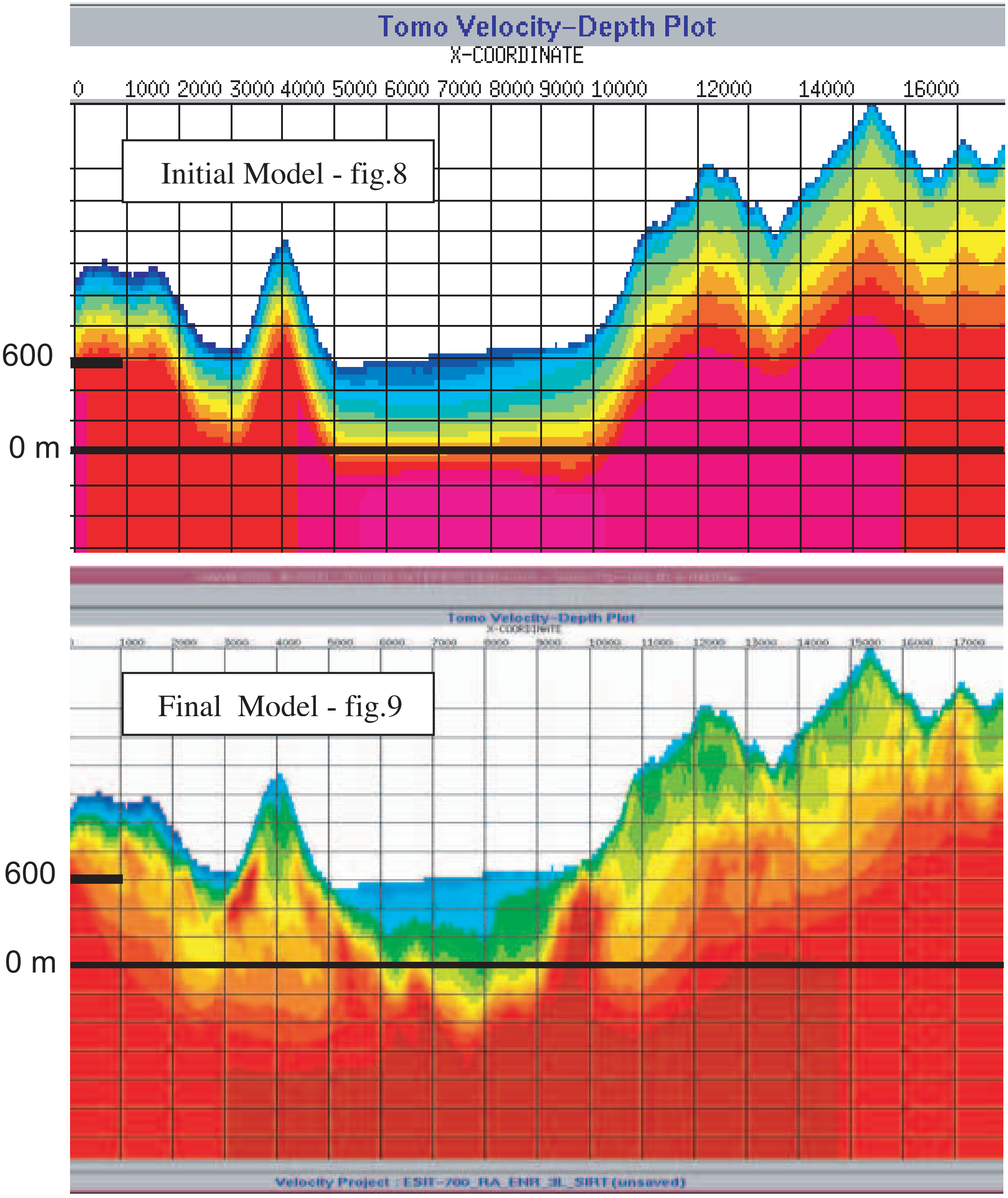
– A detailed interpretation of the shallower part of the seismic section, by removing noise and time imaging limitations, that are typically the limit of the conventional seismic TWT representation.

– A new robust 2D seismic image able to contribute to the knowledge of the Val d'Agri significantly.

5. Integrated 2D interpretation of seismic and resistivity images across the «Val d'Agri graben»

The integrated interpretation of the 2D near surface tomography velocity/depth seismic section with the 2D HR resistivity profile sensibly contributed to:

– The reconstruction of thicknesses and lithology of the most recent sediments of the valley (figs. 11 and 12).



Figs. 8-9. Near surface tomography – initial and final velocity/depth models.

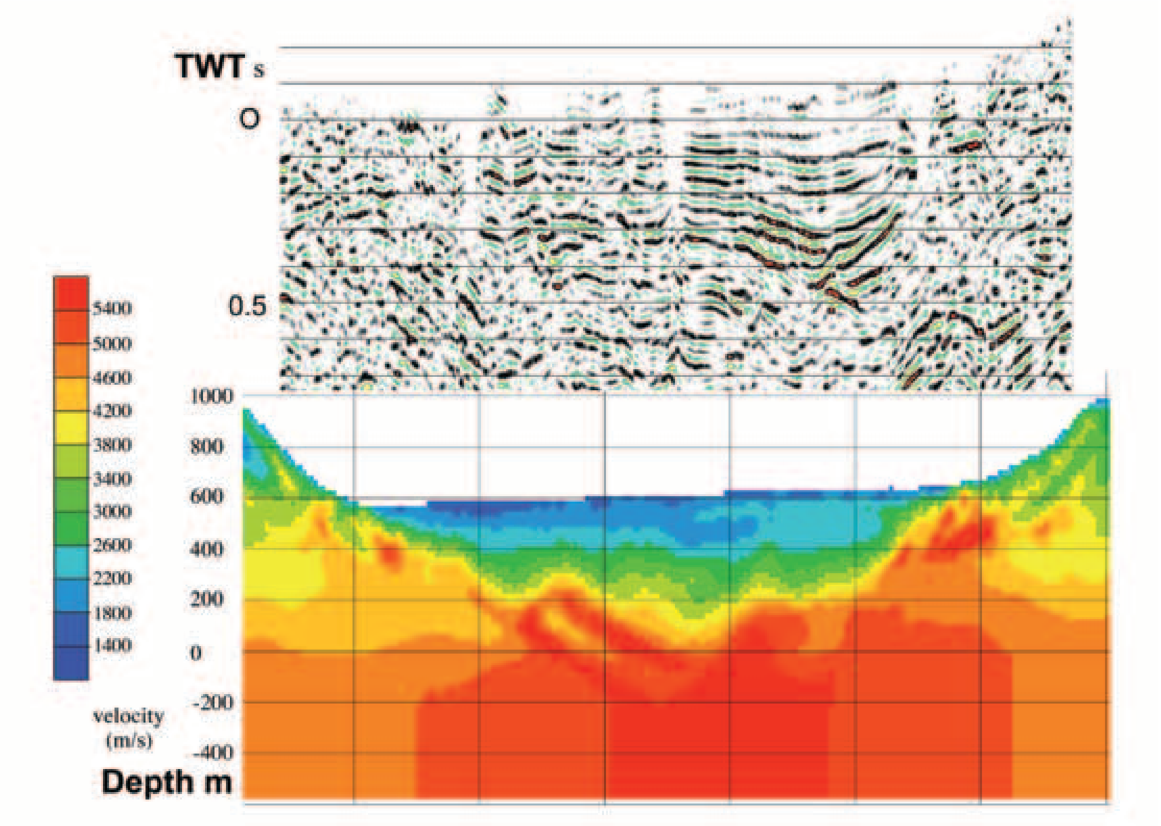


Fig. 10. Conventional time seismic *versus* tomography velocity/depth section.

– The knowledge of the structural setting of the valley (figs. 13 and 14).

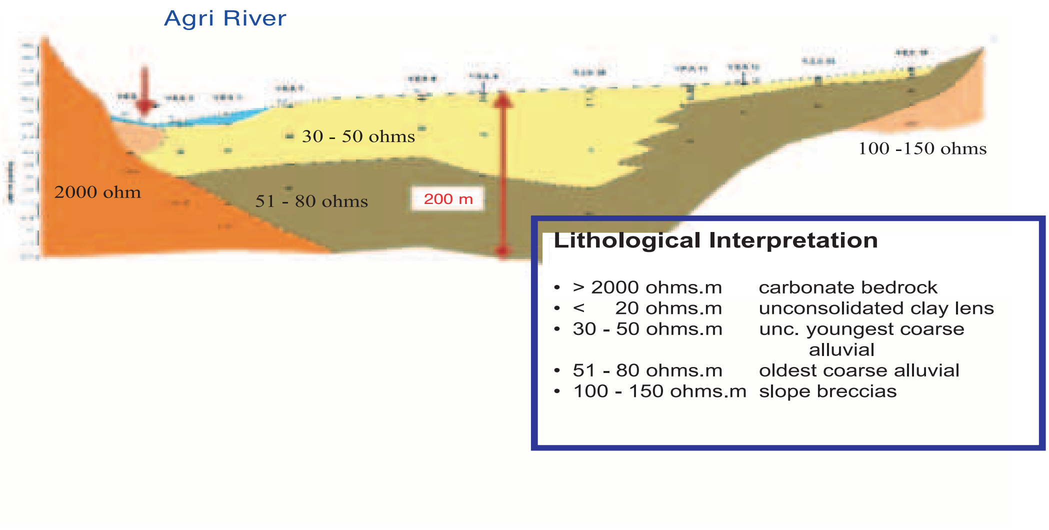
In fig. 11**,** the 2D geoelectrical profile is displayed and the lithological interpretation of the main resistivity contrasts is reported. This section was obtained by manual interpolation of 1D HR measurements.

The penetration of the resistivity profile is about 200 m. The western border of the valley is associated to the presence of a «carbonate bed rock» > 2000 Ω·m (Apennine platform outcrop) and its dipping high angle Pleistocene fault; while the eastern border of the valley is masked by slope breccias and derbis slope deposits 100-150 Ω·m.

Inside the valley, two coarse alluvial deposits cycles can be separated interpreting the most significant resistivity changes, and the progressive and rapid migration of the Agri River to the western border can be underlined.

In fig. 12, if the interpretation of the resistivity profile is integrated with the near surface tomography velocity/depth section, a great correspondence is present between shallow resistivity and shallow velocity contrasts, but the resolution and the penetration of the seismic image is sensibly higher than in the resistivity profile. For this reason, on the seismic tomography section it is possible to note the presence of a probable third alluvial deposits cycle (3) plus other 3 or 4 alluvial deeper cycles to about 800 m of depth.

The «perfect» correspondence between resistivity and velocity contrasts is probably due to the progressive compaction of the sediments



Lithological Interpretation

> 2000 ohms.m	carbonate bedrock
< 20 ohms.m	unconsolidated clay lens
30 - 50 ohms.m	unc. youngest coarse alluvial
51 - 80 ohms.m	oldest coarse alluvial
100 - 150 ohms.m	slope breccias

Fig. 11. HR resistivity *versus* lithology.

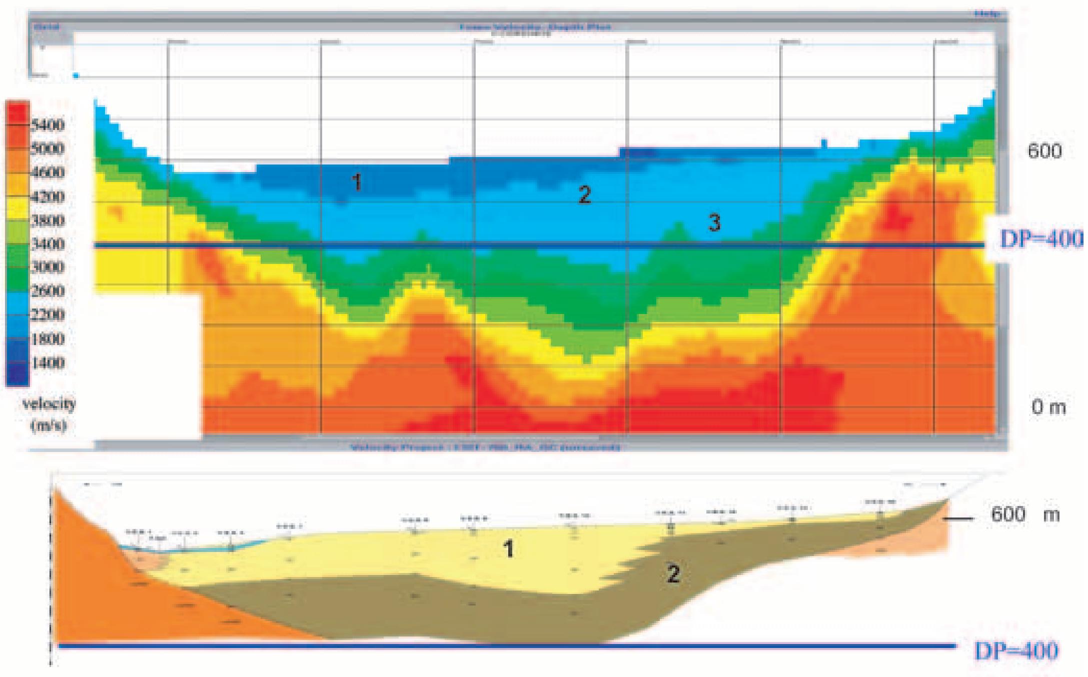


Fig. 12. HR resistivity *versus* lithology.

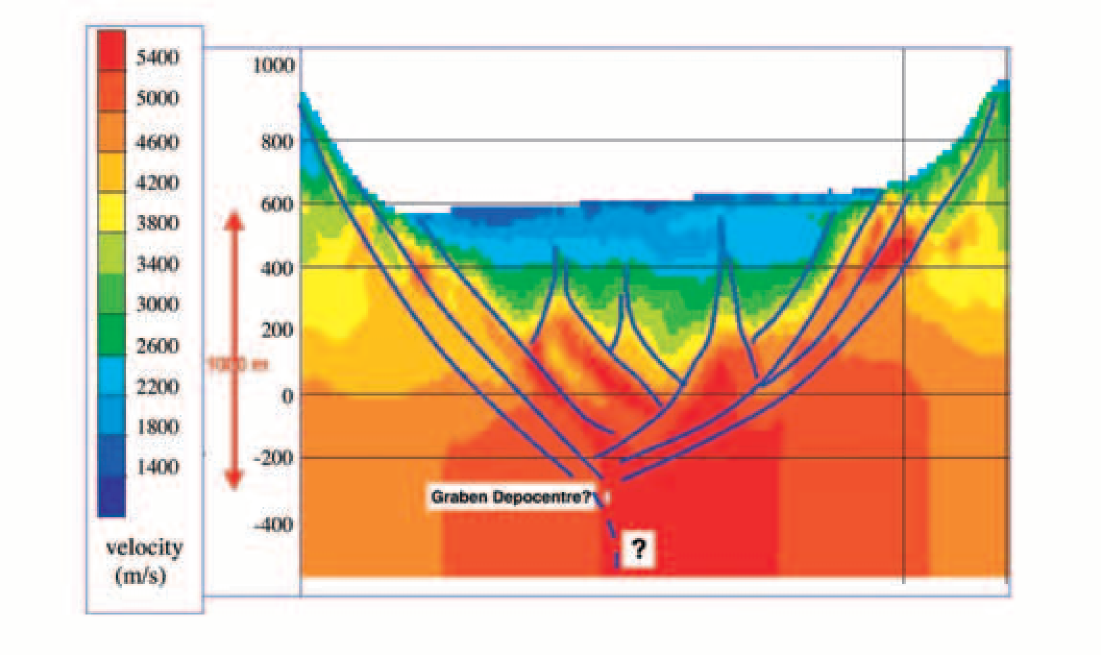


Fig. 13. Near tomography velocity – depth section – structural interpretation of the Val d'Agri graben.

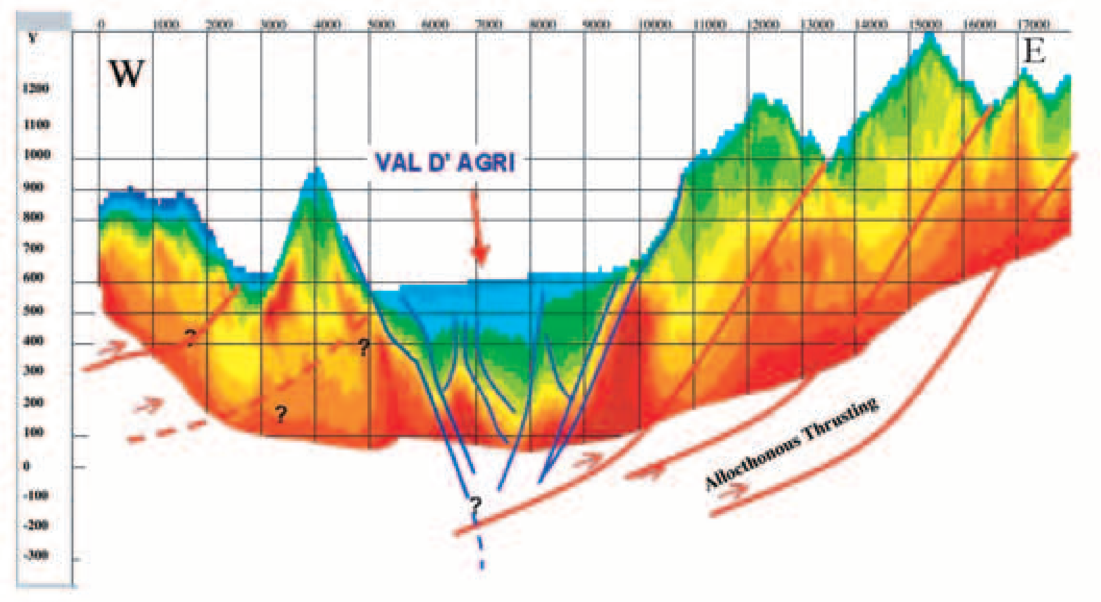


Fig. 14. Near surface tomography velocity – depth section – structural interpretation of the Val d'Agri graben in the wider context of the Apennine trust setting.

and to the presence of a progressive higher coarse deposit facies with the depth.

The variation of the sedimentary thickness inside each alluvial cycle could indicate that during the initial phase of the graben opening (alluvial cycle 3) the eastern border of the valley was deepening more quickly than the western one. Instead, during the youngest phase of the graben evolution there was an important inversion of the phenomena and the valley seems now deepening more quickly in the western ward.

This hypothesis is supported by the seismic reflection TWT image of the valley (fig. 10) and by the robust correlation with the HR resistivity model (fig. 11).

The high ray coverage and the redundant high data density are in favour of the below lithological interpretation (fig. 12) and exclude to have an apparent multi-layering «artifact because of poor data resolution, or inadequate modeling».

In fig. 13, a possible structural interpretation of the seismic tomography image of the valley is represented. The structural setting of the Val d'Agri graben is quite characteristic. The faulting system of the valley is now imaged while it is still inadequately imaged on the TWT conventional seismic (fig. 10).

The «graben» is now relatively symmetric and clearly controlled by SSW and NNE dipping high angle faults. The actually active faulting is probably located along the western margin of the valley, where this potential active tectonic tilting could also explain the lateral migration of the Agri river to west. In the central part of the valley the faulting system can be designed following the distribution of the velocity changes. This faulting system was partially active until now and just sealed by the most recent thin alluvial sediments.

From the structural point of view, the Val d'Agri graben could be interpreted as a «negative flower thrust» due to the transpressive and distensive late Apennine tectonic phase, having its depocenter at around 1000 m of depth.

In fig.14, this is quite clear when the entire «near surface seismic tomography profile» is displayed and interpreted**.**

Here, it is possible to have a more regional 2D view of the «Val d'Agri graben« and insert it in the wider geological context of the «Apennine thrust setting». The graben is young and limited in depth lateral extension.

Along the entire seismic near surface tomography section it is also possible to note that some of the normal faults of the graben (in particular along its western margin) could interest the deep allochtonous «Lagonegro units» too. It is clear that the hypothetical extension of the main thrusts below the resolution limit of the tomography image is purely speculative.

6. Conclusions

Conventional seismic data contain information that can be lost, if they are not processed and displayed properly. This is the case of the Val d'Agri, where the quality of same seismic data set can be considered average, if processed and displayed by conventionally time wiggle – variable area images; or very detailed and high resolution, if processed differently. This is the case of the conventional seismic first break arrival tomography.

Near surface tomography of conventional seismic first break arrivals can be used as an innovative interpretation tool, where rough terrain, seismic noise and structural complexity negatively influence the time seismic image and the seismic visibility.

It is certainly a very efficient high resolution illumination of the shallower part of the seismic information and it is a very robust representation of the near subsurface, directly in depth.

Shallow noise, scattering, absorption; static corrections and shallow imaging pitfalls can be very well solved by near surface tomography data processing.

The Val d'Agri subsurface was never illuminated by conventional seismic images in the past.

As a consequence, seismic tomography has incidentally given a strong contribution to the knowledge of the structural setting and lithology in «Val d'Agri graben».

A very detailed reconstruction of the Val d'Agri graben could be made by the near surface tomography of the most part of the large seismic data set present in the area. However, a good near surface tomography resolution can be obtained where the acquisition offsets are sufficiently long.

Offsets > 2500-3000 m are absolutely required to allow an efficient near surface tomography processing of seismic first arrivals to about 1000 m of depth. Unfortunately this is not the case for a lot of vintage seismic data acquired in the past in the area.

HR resistivity information mainly contributed to the lithological identification of the shallower velocity changes in the near surface tomography seismic section. However, the integrated interpretation of geoelectrical and seismic tomography images was crucial to allow the reconstruction of thickness, lithology and alluvial cycles distribution of the most recent sediments of the valley.

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REFERENCES

CERVENÝ, V., I. MOLOTKOV and I. PŠENCĬK (1977): *Ray Method in Seismology*, University of Karlova, Prague, Czechoslovakia.

DELL'AVERSANA, P., S. MORANDI, L. IMPROTA and A. ZOLLO (1999): *Tomographic Images from «Global Offset» Seismic Data Inversion in Southern Apennines*, ext. abstract 61th EAGE Conference, Helsinki, 6-34.

DELL'AVERSANA, P., E. CERAGIOLI, S. MORANDI and A. ZOLLO (2000): A simultaneous acquisition test of high density «Global Offset» seismic in complex geological settings, *First Break*, **18**, 87-96.

HAMPSON, D. and B. RUSSELL (1984): First break interpretation using generalised linear inversion, *J. Can. Soc. Explor. Geophys.*, **20** (1), 40-54.

HERRERO, A., L. IMPROTA, P. DELL'AVERSANA and S. MORANDI (2000): 2D non linear travel time tomography by multi scale search: imaging an overthrust structure in Southern Apennines (Italy) S7ID-08 Fall meeting 15-19, 2000 S. Francisco, California, supplement to *Eos*, *Trans.*, *Am. Geophys. Union*, **81** (48).

HIPPOLYTE, J.C., J. ANGELIER and F. ROURE (1994a): A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy), *Tectonophysics*, **230**, 199-210.

HIPPOLYTE, J.C., J. ANGELIER, F. ROURE and P. CASERO (1994b): Piggyback basin development and thrust belt evolution: structural and paleostress analysis in the Southern Apennines, *J. Struct. Geol.*, **16** (2), 159-173.

ZHU, X., D.P. SIXTA and B.G. ANGSTMAN (1992): Tomostatics: turning ray tomography plus static corrections, *The Leading Edge*, **11**, 12, 15-23.

ZHU, X., G.A. BURKE and D.P. SIXTA (1998): Overthrust imaging with tomo-datuming: a case study, *Geophysics*, **63** (1), 25-36.