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3D Model of the active extensional fault system of the high Agri River valley, Southern Apennines, Italy

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Abstract: The high Agri River valley (southern Apennines, Italy) hosts an active fault system, and a severe earthquake struck the area in 1857 (equivalent magnitude Me = 6.98; Imax = XI). In this study, we integrated surface geology with available subsurface data in order to propose a new 3D structural model for the high Agri River valley fault system. The model presented here is based on a series of published deep geological sections across the study area, using the software 2D Move and 3D Move (Midland Valley Exploration Ltd.). It displays the active extensional fault system dissecting the pre-existing southern Apennines fold and thrust belt. This region is characterised by the tectonic superposition of carbonate platform and pelagic basin allochthonous units onto a several km-thick carbonate platform succession representing the underthrusting foreland sequence. The detachment between the allochthon and the buried carbonate platform succession is marked by a several hundreds of metres thick mélange zone which consists mainly of intensely deformed and overpressured deepwater mudstones and siltstones.

The 3D model shows that, at surface, the valley is asymmetric, with the most relevant normal faults, as well the maximum thickness of Quaternary alluvial deposits, located along its northeastern side. Locally, minor antithetic faults generate secondary grabens. All these faults occur only in the shallow brittle layer. At depth, a normal fault cuts the top of the deeper unit just below the central part of the Quaternary plain, and does not continue in the tectonic units above. This SW-dipping feature, extending for about 20 km into a WNW-ESE direction, appears to be the most probable deep structure responsible for the development of the active fault system. Therefore, it is also likely to be the source of strong earthquakes such as the 1857 event. The 3D model outlines the mechanically fundamental role played by the ductile mélange zone, which controls the modes of fault propagation from the deep brittle layer to the shallow (allochthonous) one.

Introduction

The high Agri River valley (Alta Val d'Agri, Lucania, southern Italy; Fig. 1a) is one of the most significant areas of the southern Apennines from a seismotectonic point of view. An active fault system is hosted in the valley and one of the most destructive earthquakes in the Italian history struck the area in 1857 (equivalent magnitude, derived from intensity data by applying the method proposed by Gasperini et al., 1999: Me 6.98; maximum intensity of damage, expressed according to the MCS scale: Imax XI; Gruppo di Lavoro CPTI, 1999).

At present, no focal mechanisms are available for the study area, neither for the too old 1857 event, nor for the low and scattered instrumental seismicity recorded in recent years (ING-GNDT, 2001; Di Bucci, unpublished data). Therefore, all the different models suggested for the seismogenic structure potentially responsible for the 1857 earthquake are based on geological surveys, geomorphology, mesostructural analysis, as well as macroseismic data. A first hypothesis was proposed by Pantosti and Valensise (1988). They suggested a NW-SE striking, NE-dipping normal fault of a length exceeding 55 km (probably formed by two sub-segments). This model was mainly based on geomorphological and historical data. Again, geomorphological studies and historical data led Benedetti et al. (1998) to a different model. They outlined the noticeable development of Quaternary normal faults along the northeastern side of the high Agri River valley (Fig. 1b-e) and suggested that these are directly related with the seismogenic structure of the 1857 event. In this case, the master fault should also be NW-SE oriented, but SW-dipping. This later interpretation is also adopted by Michetti et al. (2000). Recent tectonic displacement on the faults located along the northeastern side of the valley was documented by Giano et al. (2000), who recognised Upper Pleistocene paleosoils involved in faulting. The importance of these faults for the present-day tectonic activity of the area was also outlined by Cello et al. (2000), who suggested a left-lateral strike-slip motion along a N120°-oriented fault system.

This short review shows that all the models are based on surface data and that, at least for the high Agri River valley region, this kind of data alone is not sufficient to identify the geometry of the seismogenic structure (strong earthquake hypocentres in the southern Apennines usually occur at a depth of about 10 km; Boschi et al., 1993). However, a relatively large amount of published subsurface data is available for the study area, which has been the subject of intense hydrocarbon exploration and production (e.g. Mostardini and Merlini, 1986; Carbone et al., 1991; Casero et al., 1991; Roure et al., 1991; Mazzoli et al., 2000; 2001; Menardi Noguera and Rea, 2000; Morandi and Ceragioli, 2000, 2002; Butler et al., in press). In this work we integrate surface geology with published

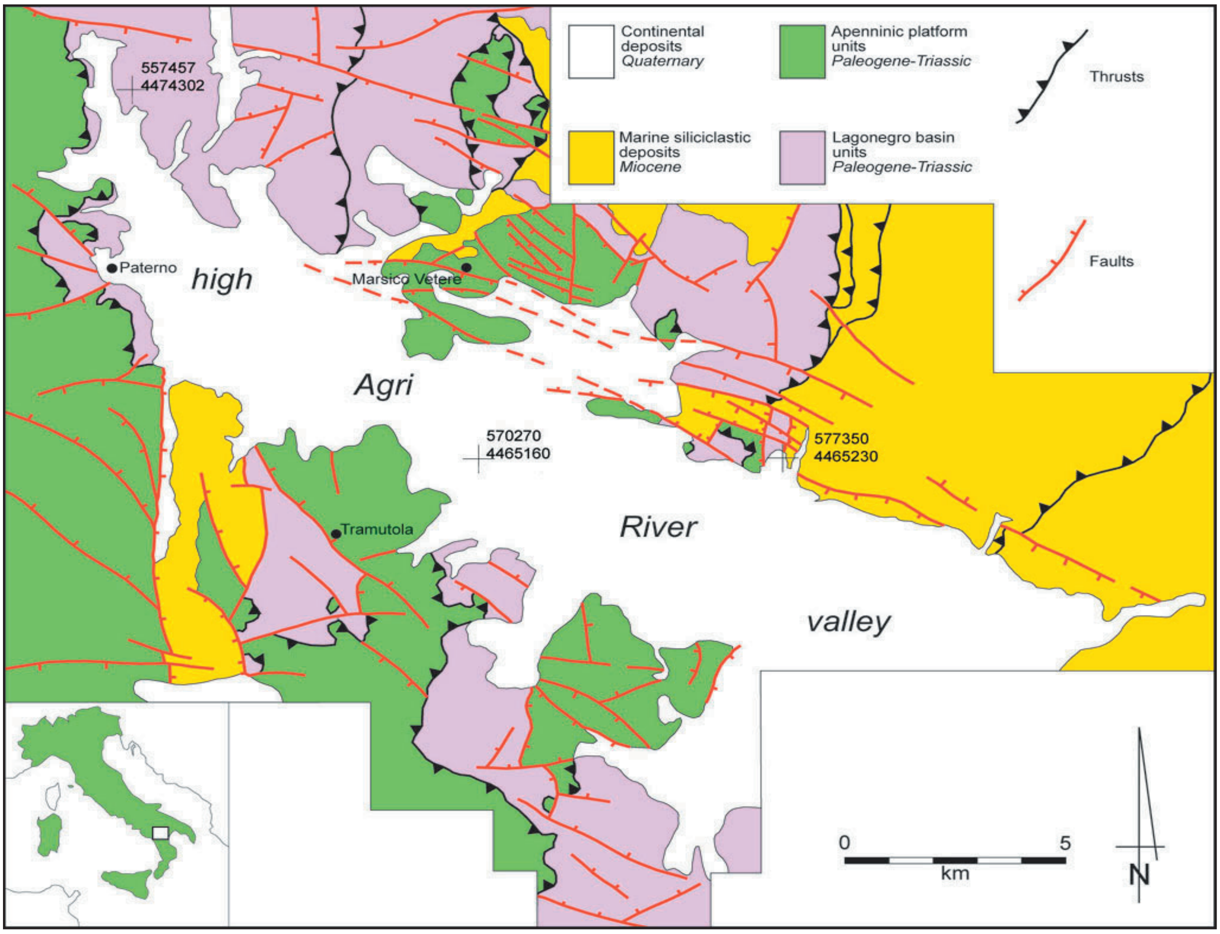

Figure 1(a). Schematic geological map of the high Agri River valley area.

subsurface data and propose a new 3D model for the fault system. This model (Figs. 2-6) was built, based on a series of deep geological sections across the study area, using the software 2D Move and 3D Move (Midland Valley Exploration Ltd.).

We suggest that, at depth, the high Agri River valley active fault system is related to a SW dipping master fault; this fault was probably responsible for the 1857 earthquake (Fig. 2). Our model represents the first attempt to reconstruct the 3D geometry of an active fault system in a seismic area such as Italy and, therefore, also constitutes a challenge for seismic hazard and scenarios studies.

Geological setting

The high Agri River valley (Fig. 1a) is a WNW-ESE oriented intramontane basin located in the axial zone of the southern Apennines mountain belt. Here, a Quaternary fault system dissects the pre-existing fold and thrust belt. The latter is characterised by the tectonic superposition of allochthonous units, completely detached from their original substratum, onto the foreland succession of the Apulian Platform. This consists of a 6-7 km thick, Mesozoic-Tertiary shallow-water carbonate succession, stratigraphically overlain by upper Messinian and/or Pliocene terrigenous marine deposits. The buried Apulian carbonate rocks appear to be deformed by thick-skinned inversion/thrust structures (e.g. Mazzoli et al., 2000; 2001).

The allochthonous units, exposed at surface, consist of Mesozoic-Paleogene peritidal carbonate platform (Apenninic Platform) and pelagic basin (Lagonegro Basin) units unconformably overlain by Miocene siliciclastic strata (Fig. 1a). These rocks are involved in mainly NW-SE to N-S trending folds and thrusts, which formed during Late Oligocene-Neogene shortening (Mazzoli et al., 2001).

The detachment between the allochthon and the buried Apulian unit is marked by a mélange zone, several hundreds of metres thick. This unit (Mazzoli et al., 2001) dominantly consists of intensely deformed and overpressured deepwater mudstones and siltstones, with minor sandstones and limestones. Biostratigraphic data indicate a Miocene-Lower Pliocene age for the bulk of the sediments within this interval (Mazzoli et al., 2001, and references therein). This unit, representing the major décollement at the base of the allochthon, is interpreted to include Mio-Pliocene foredeep deposits incorporated within the décollement zone as the advancing fold and thrust belt over-rode its foreland basin (Mazzoli et al., 2001).

This setting is shown in the 3D model of Figs. 2-6. For the sake of simplicity, as it was not relevant to the present study, the internal structure of the allochthon is not shown in the model.

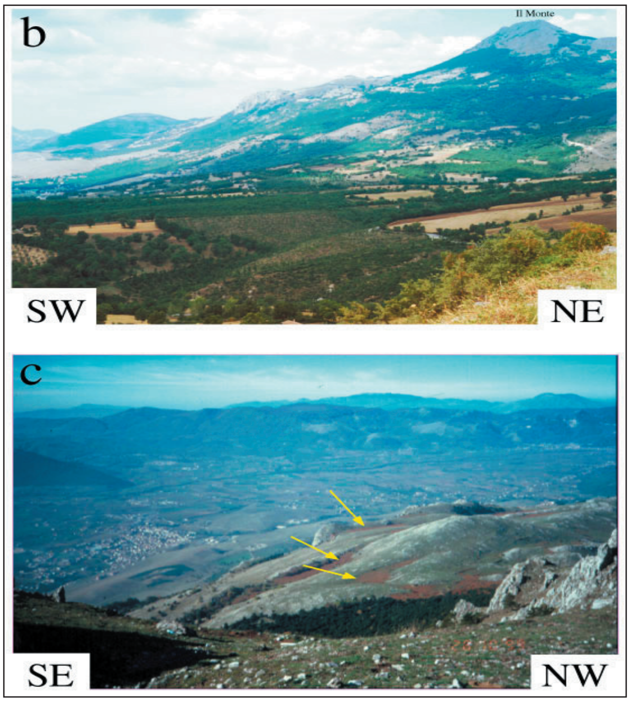

Figure 1(b). View of the northeastern side of the high Agri River valley, showing stepped morphology controlled by extensional fault scarps. **(c)** View of the valley from 'Il Monte', showing southwestward down-faulting of karst surfaces (arrowed) in Mesozoic limestones.

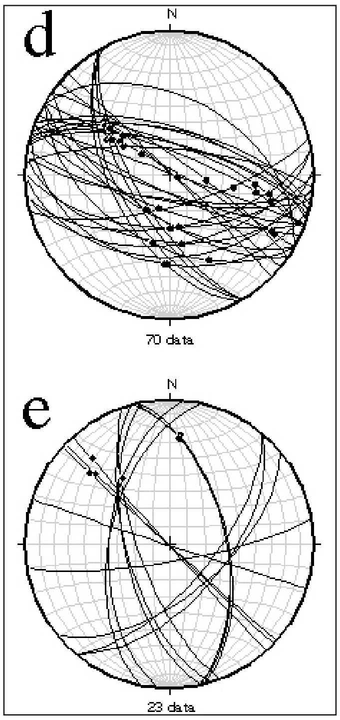

Figure 1(d)-(e). Orientation data for Quaternary faults (lower hemisphere, equal-area projections). Great circles are fault planes from the northeastern (d) and southwestern (e) sides of the valley. Black dots are slip vectors determined from shear fibres or striae on slickenside surfaces. Fault kinematics is extensional or oblique-slip with extensional components in all cases. Compare dispersed fault pattern from the southwestern side of the valley (e) with consistent WNW-ESE dominant trends recorded from the northeastern, fault-bounded valley flank (d).

Structural model

Model realisation

The 3D structural model was constructed by applying the software 3D Move to a series of geological sections across the study area. For their shallow part, these sections were drawn based on a detailed field survey on the Quaternary fault system of the high Agri River valley. Available information obtained by field structural analysis was used to constrain the geometry of surface faults (Figs. 3 and 4). The part of the cross-sections used to build up the structural model at depth (Figs. 5-6) was drawn based on the analysis and integration of the large amount of subsurface information (deep geological sections, borehole and seismic reflection data) published on the high Agri River valley hydrocarbon province (Mostardini and Merlini, 1986; Carbone et al., 1991; Casero et al., 1991; Roure et al., 1991; Mazzoli et al., 2000; 2001; Menardi Noguera and Rea, 2000; Morandi and Ceragioli, 2000, 2002; Shiner et al., 2002; Butler et al., in press). Examples of hydrocarbon well log and seismic reflection data are shown in Figs. 7-9.

Seismic response within the study area is highly variable, ranging from moderate to poor. It is controlled by a number of factors commonly observed to limit seismic quality within fold and thrust belts, namely: extreme topographic variation, highly variable surface geology, complex structures commonly characterised by steep dips, strong lateral variations in velocity resulting in "pull-up" phenomena, and the presence of marked velocity inversions, particularly at the base of the allochthon (La Bella et al., 1996; Dell'Aversana et al., 2000). Given this, the only seismic event that can be identified and mapped with a moderately high level of confidence based on its seismic character alone is the Top Apulian Platform reflector. This event is seismically characterised by a high-continuity, high amplitude, low frequency singlet or doublet, arising either directly from the Top Apulian carbonates or by interference between reflections deriving from the strong positive reflection coefficients at the top of the platform and at the top of the Pliocene clastics (Figs. 7-8). Fig. 7 shows an interpretation of the Top Apulian Platform reflector in a typical seismic line from the Lucania area. A main low-angle detachment separates the Pliocene sequence, stratigraphically overlying the Apulian carbonates in the footwall, from the allochthonous units in the hanging wall. This detachment – and the associated mélange zone (Fig. 9a) – also divides the section into two parts showing different styles of deformation: the allochthon, characterised by low-angle thrust surfaces, and the Apulian domain, characterised by steeply dipping reverse faults. The base of the Apulian platform is also visible as a strong reflection in some areas and can sometimes be used to guide the interpretation of the top platform (Fig. 8). This deep seismic event was interpreted by reference to deep wells drilled in the Apulian foreland. For instance, the Puglia 1 well drilled 6112 m of shallow water carbonates and evaporites before penetrating an unconformity underlain by about 1000 m of continental to transitional argillites and sandstones (Fig. 9b).

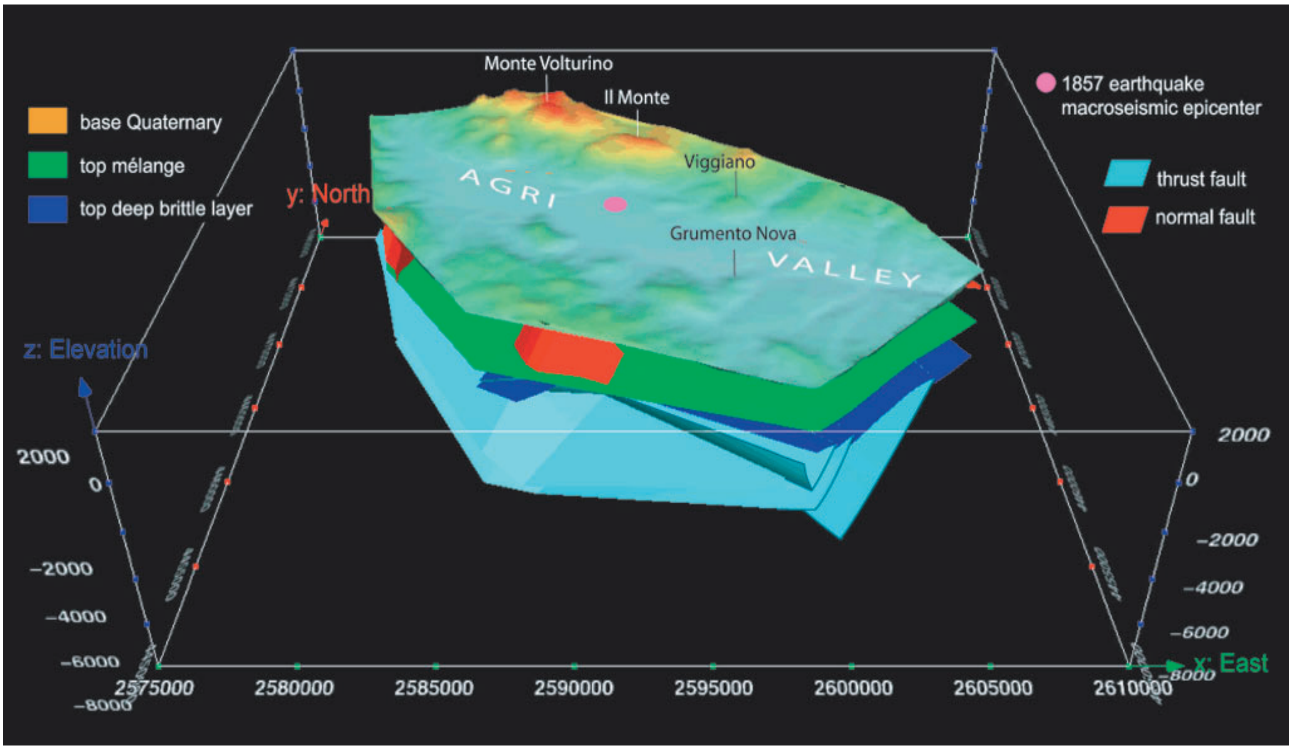

Fig. 2. Three-dimensional structural model of the high Agri River valley area: general view from the South. Location of macroseismic epicentre of the 1857 earthquake (after Gruppo di Lavoro CPTI, 1999) also shown.

Model description

The shallow part of the 3D structural model shows how the Agri River basin, filled with Quaternary fluvio-lacustrine, alluvial fan and slope deposits, is tectonically controlled by WNW-ESE striking, high-angle faults (Figs. 3 and 4). These, according to Giano et al., (2000), acted as left-lateral strike-slip structures during the Early Pleistocene and were later reactivated, mainly as normal faults, in Middle Pleistocene-Holocene times (latest documented extensional activity dated at 40-20 ky; Giano et al., 2000). At surface, this fault system is mainly developed along the north-northeastern side of the valley (Figs. 1d-e and 4). Here, it produced significant tilting of the bedding in a domino fashion, as well as an asymmetric filling of the basin, which shows a maximum thickness along the same side (Morandi and Ceragioli, 2000). At depth, a recent (i.e. post-thrusting) normal fault (with a secondary splay) offsets the buried Apulian unit (Fig. 6). This fault develops for about 20 km in WNW-ESE direction, dips toward SSW with an angle of ca. 60° and shows a total vertical displacement of about 350 m referred to the Top Apulia Platform horizon. This structure, however, does not link directly with the extensional structures in the overlying allochthon (Fig. 6).

The relationships between shallow and deep structures reconstructed in the study area can be fully appreciated in the animation of Fig. 10.

Further and independent constraints on the reconstructed relationships between surface features and deep faults in the high Agri River valley are also provided by fluid inclusion data. Samples from fault rocks exposed in the study area contain fluid inclusions composed of very low-salinity water (Cello et al., 2001). This contrasts with data from similar basin-bounding faults exposed in other areas of the Apennines (e.g. the Central Apennines). The latter contain fluid inclusions composed of high salinity water, which has been interpreted as a result of fluid upwelling from a depth of 4-6 km (Cello et al., 2001). In our study area, the lack of hydrocarbon and/or high-salinity water inclusions rules out a direct connection of the surface faults with the deep (Apulian) reservoir, while it is compatible with the interpretation that surface faults are confined within a shallow level.

Discussion

The structural setting of the study area can be schematised as a superposition of three roughly subhorizontal layers (Fig. 6). The shallow (allochthonous Apenninic Platform and Lagonegro Basin units) and the deeper ones (Apulian Platform unit) are characterised by a brittle behaviour. However, the intermediate layer (the mélange) diverges from this behaviour. In fact the data exposed above indicate that, from a mechanical point of view, it is most probably similar to another water-saturated, clay-rich décollement level, well known from the southern Apennines (Roure et al., 1990): the so-called “Argille varicolori” (varicoloured shales) formation (Sgrosso, 1988; Patacca et al., 1992b; Di Bucci et al., 1996; Corrado et al., 1998). Due to fluid overpressure and circulation, these deposits show a ductile behaviour that not only controls the development of one of the most important detachment levels in the Apennines (Patacca et al., 1990; 1992a; Corrado et al., 1997; Mazzoli

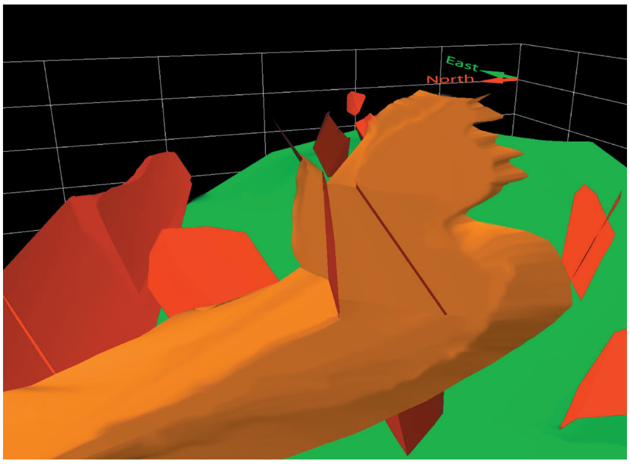

Figure 3. Three-dimensional structural model: detail of faulted base Quaternary on the NE side of the valley (view from WNW). Legend in Fig. 2.

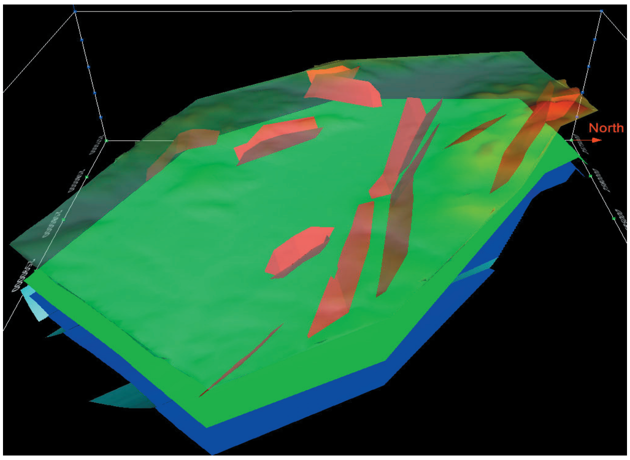

Figure 4. Three-dimensional structural model: view from the East, showing (in red) shallow fault pattern (translucent topographic surface; base Quaternary not shown). Legend in Fig. 2.

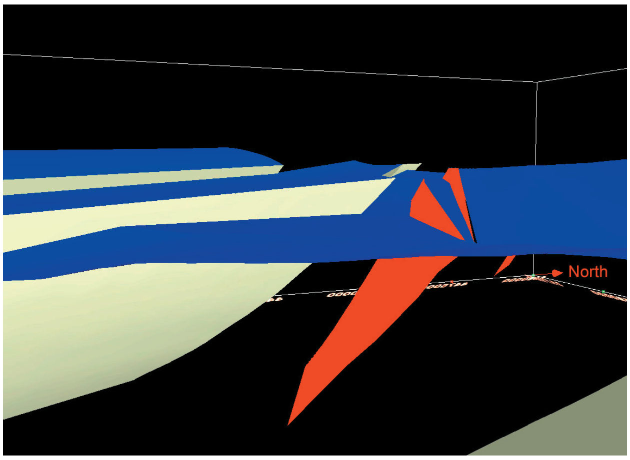

Figure 5. Three-dimensional structural model: faults within the deep brittle layer (view from SE; top of the deep brittle layer in dark blue, thrust faults in sky-blue, normal faults in red). Legend in Fig. 2.

et al., 2000) but, occasionally, also generates mud diapirs (Roure et al., 1990).

The behaviour of brittle-ductile-brittle multilayers has been extensively analysed by analogue modelling (e.g. Richard, 1990; Allemand and Brun, 1991; Richard and Krantz, 1991; Mandl, 2000) as well as in real cases (e.g. Nalpas and Brun, 1993). When the ductile unit shows a sufficient thickness, normal faults do not directly propagate across it from the deep to the shallow brittle beds. Deep-seated extension propagates toward the surface through the ductile layer, which flows both toward the footwall and the hanging wall of underlying faults. In this way, the ductile layer acts as a decoupling and accommodating horizon. Its presence allows the surface fault pattern to be different from the subsurface pattern, as already outlined by Vendeville et al. (1987). Surface evidence of extension is then given by a wide, asymmetric pattern of normal faults that are more numerous, unconnected and shifted with respect to the deep parent faults.

All these features can be recognised in the model of Figs. 2-6, and provide an interpretative key for the development of the extensional system of the high Agri River valley. At surface, the valley is asymmetric, showing the most relevant Middle-Upper Pleistocene normal faults, as well as the maximum thickness of the coeval alluvial deposits (Morandi and Ceragioli, 2000; 2002), along its north-northeastern side. Locally, minor antithetic faults generate secondary grabens. All these faults develop only in the shallow allochthonous units, made up of carbonate platform and pelagic basin rocks and characterised by brittle behaviour.

At depth these faults do not crosscut the mélange zone, nor involve the top of the Apulian unit, which remains uninterrupted in correspondence with the hypothetical continuation of the main surface faults.

An important normal fault cuts, instead, the top of the Apulian unit just below the central part of the Quaternary plain, and does not continue in the tectonic units above. As previously mentioned, this fault extends for about 20 km into a WNW-ESE direction and is SSW-dipping; it follows that the most developed faults at surface are those synthetic with respect to it. The deep fault shows a vertical displacement of about 350 m, and post-dates thrusting within the Apulian domain that, in this area, is Late Pliocene-Early Pleistocene in age (Cello and Mazzoli, 1999; Mazzoli et al., 2001, and references therein). Therefore, this fault acted between Middle Pleistocene and present-day. Being conservative, a vertical displacement of 350 m in ca. 750 ka gives a vertical separation rate of ca. 0.47 mm/y, corresponding to a slip rate of about 0.54 mm/y. This value is comparable with the slip rates calculated, based on surface data alone, for many other active extensional faults in the Apennines (Galadini and Galli, 2000, and references therein).

According to the model presented in this work and also considering age, displacement and location of this fault, it appears to be the most probable deep structure responsible for the development of the active fault system and the related basin of the high Agri River valley; as a consequence, it is likely to be the source of

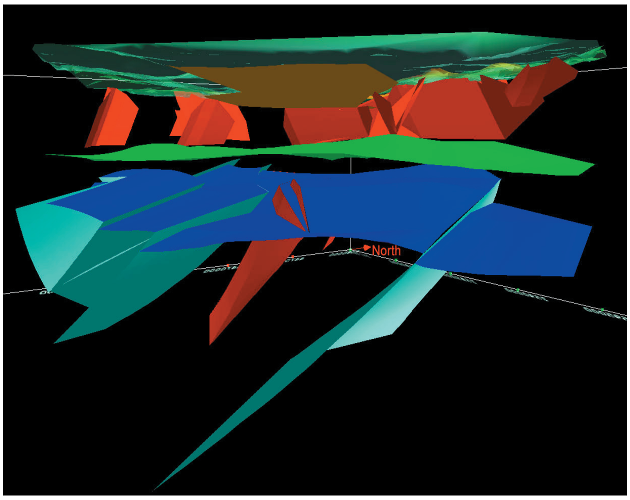

Figure 6. Three-dimensional structural model: view from SE, showing lack of continuity between normal faults in the shallow layer (i.e. the allochthon) and those in the deep brittle domain. Legend in Fig. 2.

strong earthquakes such as the 1857 event. This is also compatible with a seismic sequence which occurred in 1996 at a depth between 4 and 7 km below the SW-side of the high Agri River valley (Ciaccio et al., 2001), roughly in correspondence with the most likely location of the south-eastern termination of this fault in the core of the Apulian unit.

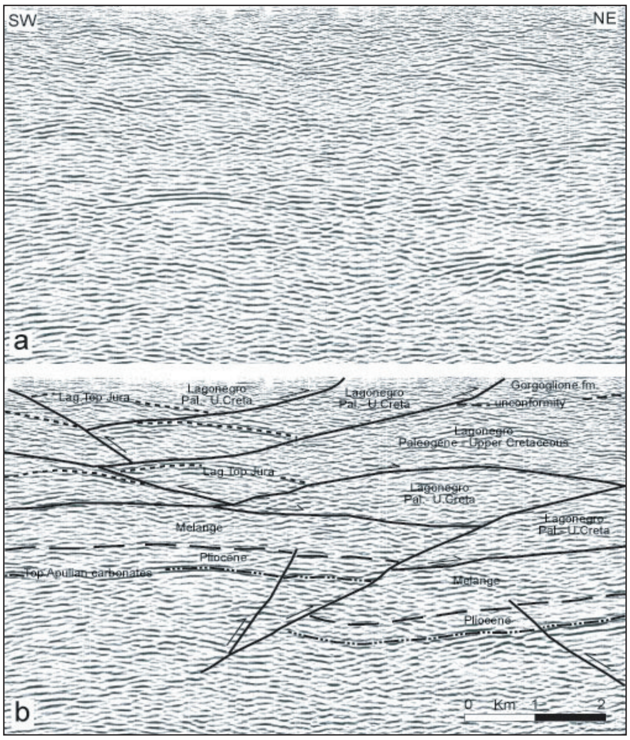

Figure 7. (a) Stack seismic line across central Lucania (from Mazzoli et al., 2000; precise location and depth in two-way-time are confidential). **(b)** Interpretation, showing allochthonous thrust sheets overlying the Apulian platform carbonates.

Concluding remarks

The occurrence of a buried ductile mélange zone intercalated within the Apennine thrust structure appears to exert a major control on the active extensional fault system which developed in the high Agri River valley of southern Italy. As shown by the 3D structural model presented in this paper, there is no direct brittle connection, across such a mélange zone, between the deep (seismogenic) structure and the active faults exposed at surface. Therefore, a ‘soft-linkage’ can be inferred to occur across the mélange zone between the deep master fault and the surface fault strands.

Our study emphasises the fundamental importance of detailed 3D reconstructions of the tectonic setting of the Apennine chain in order to achieve a better understanding of the active fault systems in the Italian peninsula. For some of these systems, in fact, models based on surface data alone do not offer a univocal solution. Moreover, seismic events like the 1980 Irpinia (Italy) earthquake, caused by the activation of at least three main faults both NE- and SW-dipping (Boschi et al., 1993), outline the real complexity of the seismic sources. From this point of view, 3D models of active fault systems in seismic regions represent a possible upgrade with respect to the simplified single fault models usually adopted in seismic hazard and scenario studies, providing a more realistic source for destructive earthquakes.

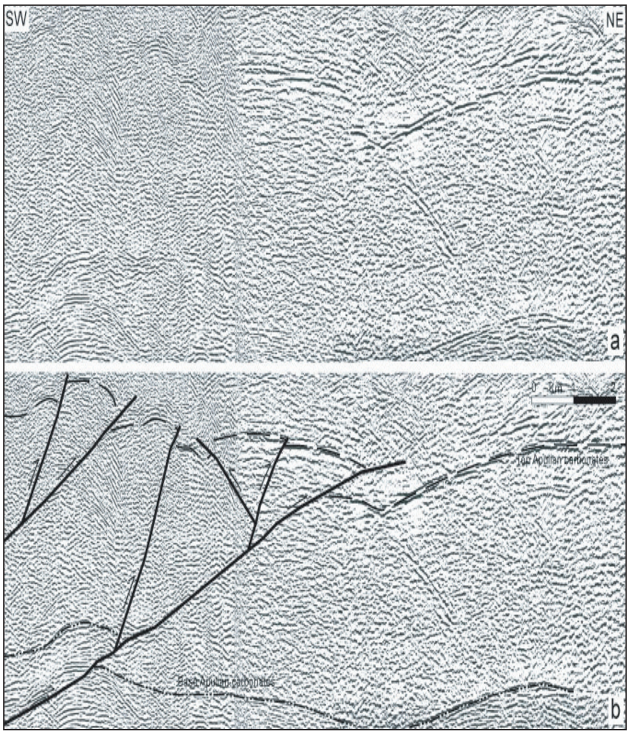

Figure 8. (a) Stack seismic line across southern Lucania (from Mazzoli et al., 2000; precise location and depth in two-way-time are confidential). **(b)** Interpretation, showing reflectors ascribed to “top” and “base” Apulian platform carbonates.

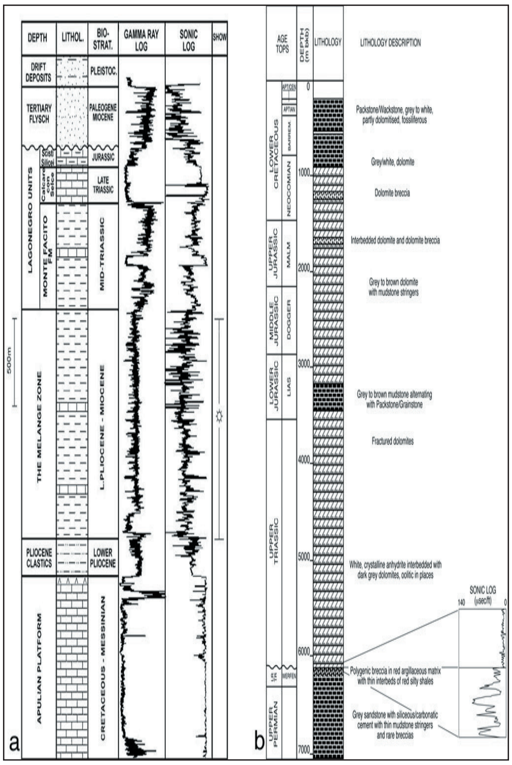

Figure 9. (a) Typical hydrocarbon well in the Lucania area of the southern Apennines, showing thick mélange zone at the base of the allochthonous Lagonegro and Tertiary flysch units (from Butler et al., in press). **(b)** Simplified stratigraphic log of the Puglia 1 well drilled in the Apulian foreland. Inset shows detail of sonic log around the base of the shallow-water carbonate succession (from Mazzoli et al., 2000).

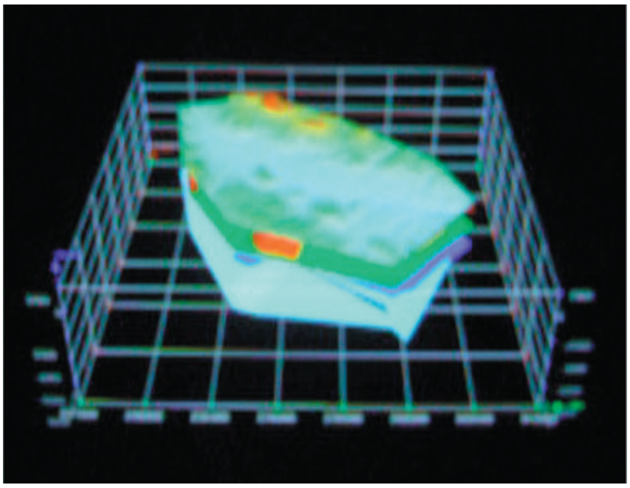

Figure 10. Animation of 3D model. The animation starts looking at the high Agri River valley from the South. As the model is rotating clockwise, our point of view moves to the SE. As we go down and closer to the model, we can appreciate the lack of continuity between normal faults in the shallow layer (i.e. the allochthon, overlying the green surface) and those in the deep brittle domain (bounded on top by the dark blue surface). As the model is further rotatedclockwise, our point of view progressively moves to the north and then to the NW. Also from this side, the relationships between shallow and deep faults can be observed. As the topographic surface (DEM) is removed, the top of the continental Quaternary deposits - faulted along the northeastern side of the valley - can be observed. The model is further rotated clockwise to reach the starting position (i.e. view from the South). Two formats are available: .AVI **<click to view>** (10.3 Mb, QuikTime player recommended for Mac users) and .SCM **<click to view>** (16.5 Mb ®¢ better resolution, Lotus Screencam Player; downloadable from http://www.lotus.com/products/screencam.nsf) zipped. Using Lotus Screencam you can download LotusMediaV2 plugin for Internet Explorer (version 4.0 or later).

References

Allemand, P. and Brun, J.-P., 1991. Width of continental rifts and rheological layering of the lithosphere. Tectonophysics, 188, 63-69.

Benedetti, L., Tapponnier, P., King, G. C. P. and Piccardi, L., 1998. Surface rupture of the 1857 southern Italian earthquake? Terra Nova, 10 (4), 206-210.

Boschi, E., Pantosti, D., Slejko, D., Stucchi, M. and Valensise, G., 1993. Special issue on the meeting "Irpinia dieci anni dopo", Sorrento, 1990. Annali di Geofisica, 36 (1), 351 p.

Butler, R. W. H., Mazzoli, S., Corrado, S., De Donatis, M., Scrocca, D., Di Bucci, D., Gambini, R., Naso, G., Nicolai, C., Shiner, P. and Zucconi, V., in press. Applying thick-skinned tectonic models to the Apennine thrust belt of Italy: Limitations and implications. American Association of Petroleum Geologists Memoires.

Carbone, S., Catalano, S., Lazzari, S., Lentini, F. and Monaco, C., 1991. Presentazione della carta geologica del Bacino del Fiume Agri (Basilicata). Memorie della Società Geologica Italiana, 47, 129-143.

Casero, P., Roure, F. and Vially, R., 1991. Tectonic framework and petroleum potential of the southern Apennines. In: Generation, accumulation, and production of Europe's hydrocarbons (Spencer, A. M., Ed.). Special Publication of the European Association of Petroleum Geoscientists, 1, 381-387.

Cello, G. and Mazzoli, S., 1999. Apennine tectonics in southern Italy: a review. Journal of Geodynamics, 27, 191-211.

Cello, G., Gambini, R., Mazzoli, S., Read, A., Tondi, E. and Zucconi, V., 2000. Fault zone characteristics and scaling properties of the Val d'Agri Fault System (southern Apennines, Italy). Journal of Geodynamics, 29, 293-307.

Cello, G., Invernizzi, C., Mazzoli, S. and Tondi, E., 2001. Fault properties and fluid flow patterns from Quaternary faults in the Apennines, Italy. Tectonophysics, 336, 63-78.

Ciaccio, M. G., Cinti, F. R., Cucci, L., Frepoli, A., Gervasi, A., Margheriti, L., Mariucci, M. T., Montone, P., Pierdominici, S. and Pondrelli, S., 2001. Un approccio multidisciplinare per la caratterizzazione delle sorgenti sismogenetiche nelle aree di 'lacuna sismica': primi risultati per i bacini del Pergola-Melandro e della val d'Agri. 20° Convegno Nazionale GNGTS, Abstract volume, 247-248.

Corrado, S., Di Bucci, D., Naso, G. and Butler, R. W. H., 1997. Thrusting and strike-slip tectonics in the Alto Molise region (Italy): implications for the Neogene-Quaternary evolution of the Central Apennine orogenic system. Journal of the Geological Society, London, 154, 679-688.

Corrado, S., Di Bucci, D., Naso, G., Giampaolo, C. and Adatte, T., 1998. Application of organic matter and clay mineral studies to the tectonic history of the Abruzzo-Molise-Sannio area, Central Apennines, Italy. Tectonophysics, 285, 167-181.

Dell'Aversana, P., Ceragioli, E., Morandi, S. and Zollo, A., 2000. A simultaneous acquisition test of high-density 'global offset' seismic in complex geological settings. First Break, 18, 87-96.

Di Bucci, D., Parotto, M., Adatte, T., Giampaolo, C. and Kübler, B., 1996. Mineralogia delle Argille varicolori dell'Appennino centrale: risultati preliminari e prospettive di ricerca. Bollettino della Società Geologica Italiana, 115, 689-700.

Galadini, F. and Galli, P., 2000. Active Tectonics in the Central Apennines (Italy) – Input Data for Seismic Hazard Assessment. Natural Hazards, 22, 225-270.

Gasperini, P., Bernardini, F., Valensise, G. and Boschi, E., 1999. Defining seismogenic sources from historical earthquake felt reports. Seismological Society of America Bulletin, 89, 94-110.

Giano, I., Maschio, L., Alessio, M., Ferranti, L., Improta, S. and Schiattarella, M., 2000. Radiocarbon dating of active faulting in the Agri high valley, southern Italy. Journal of Geodynamics, 29, 371-386.

Gruppo di Lavoro CPTI, 1999. Catalogo Parametrico dei Terremoti Italiani. ING, GNDT, SGA, SSN, Bologna, 92 pp.

ING-GNDT – Gruppo di Lavoro Catalogo Strumentale, 2001. Catalogo Strumentale dei Terremoti Italiani dal 1981 al 1996, 1.0 version CD-ROM.

La Bella, G., Bertelli, L. and Savini, L., 1996. Monte Alpi 3d, a challenging 3D survey in the Apennine Range, southern Italy. First Break, 14, 285-294.

Mandl, G., 2000. Faulting in brittle rocks. An introduction to the mechanics of tectonic faulting. Springer-Verlag, 434 pp.

Mazzoli, S., Barkham, S., Cello, G., Gambini, R., Mattioni, L., Shiner, P. and Tondi, E., 2001. Reconstruction of continental margin architecture deformed by the contraction of the Lagonegro Basin, southern Apennines, Italy. Journal of the Geological Society, London, 158, 309-319.

Mazzoli, S., Corrado, S., De Donatis, M., Scrocca, D., Butler, R. W. H., Di Bucci, D., Naso, G., Nicolai, C. and Zucconi, V., 2000. Time and space variability of "thin-skinned" and "thick-skinned" thrust tectonics in the Apennines (Italy). Rendiconti Lincei Scienze Fisiche e Naturali, s. 9, 11 (1), 5-39.

Menardi Noguera, A. and Rea, G., 2000. Deep structure of the Campanian-Lucanian Arc (southern Apennines). Tectonophysics, 324, 239-265.

Michetti, A. M., Ferreli, L., Esposito, E., Porfido, S., Blumetti, A. M., Vittori, E., Serva, L. and Roberts, G. P., 2000. Ground effects during the 9 September 1998, Mw = 5.6, Lauria earthquake and the seismic potential of the "aseismic" Pollino region in southern Italy. Seismological Research Letters, 71 (1), 31-46.

Morandi, S. and Ceragioli, E., 2000. Integrated interpretation of seismic and resistivity images across the "Val d'Agri" graben (Italy). VIII Workshop on Geo-Electromagnetism, Maratea (Italy), Abstract volume, 65.

Morandi, S. and Ceragioli, E., 2002. Integrated interpretation of seismic and resistivity images across the "Val d'Agri" graben (Italy). Annals of Geophysics, 45 (2), 259-271.

Mostardini, F. and Merlini, S., 1986. Appennino centro-meridionale. Sezioni geologiche e proposta di modello strutturale. Memorie della Società Geologica Italiana, 35, 177-202.

Nalpas, T. and Brun, J.-P., 1993. Salt flow and diapirism related to extension at crustal scale. Tectonophysics, 228, 349-362.

Pantosti, D. and Valensise, G., 1988. La faglia sud-appenninica: identificazione oggettiva di un lineamento sismogenetico nell'Appennino meridionale. Atti 7° Convegno Nazionale GNGTS, 205-220.

Patacca, E., Sartori, R. and Scandone, P., 1990. Tyrrhenian basin and apenninic arcs: kinematic relations since Late Tortonian times. Memorie della Società Geologica Italiana, 45, 425-451.

Patacca, E., Scandone, P., Bellatalla, M., Perilli, N. and Santini, U., 1992a. La zona di giunzione tra l'arco appenninico settentrionale e l'arco appenninico meridionale nell'Abruzzo e nel Molise. Studi Geologici Camerti, volume speciale (1991/2), CROP 11, 417-441.

Patacca, E., Scandone, P., Bellatalla, M., Perilli, N. and Santini, U., 1992b. The Numidian-sand event in the southern Apennines. Memorie di Scienze Geologiche (già Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova), 43, 297-337.

Richard, P. and Krantz, R. W., 1991. Experiments on fault reactivation in strike-slip mode. Tectonophysics, 188, 117-131.

Richard, P., 1990. Champs de failles au dessus d'un décrochement de socle: modelisation expérimentale. Mémoires et Documents du Centre Armoricain d'Etude Structurale des Socles, 34, 342 pp.

Roure, F., Casero, P. and Vially, R., 1990. Growth processes and mélange formation in the southern Apennines accretionary wedge. In: Petroleum and tectonics in the Apennines and Sicily (Roure, F., Moretti, I., Vially, R., Casero, P., Howell, D. G. and Riva, E., Eds), Institut Français du Pétrole, Internal Report n. 38195.

Sgrosso, I., 1988. Le argille varicolori del bacino molisano. Bollettino della Società Geologica Italiana, 107, 431-436.

Shiner, P., Beccacini, A. and Mazzoli., S., 2002. Thin-skinned versus thick-skinned models for Apulian Carbonate Reservoirs: constraints from the Val d'Agri Fields. Oil and Gas in Compressional Belts, The Geological Society, London, September 10-11, 2002, Abstract volume, 55.

Valensise, G. and Pantosti, D. (Eds), 2001. Database of potential sources for earthquakes larger than M 5.5 in Italy. Annali di Geofisica, Suppl. to vol. 44 (4), 180 pp., with CD-ROM.

Vendeville, B., Cobbold, P. R., Davy, P., Brun, J.-P. and Choukroune P., 1987. Physical models of extensional tectonics at various scales. In: Continental extensional tectonics (Coward, M. P., Dewey, J. F. and Hancock, P. L., Eds), Geological Society Special Publication, 28, 95-107.