

# Integration of geological and geophysical data along a section crossing the region of the 1997-98 Umbria-Marche earthquakes (Italy)

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## ABSTRACT

A geological cross-section, oriented about N80°E and crossing the Colfiorito area, struck by the 1997-98 Umbria-Marche earthquakes has been built up, integrating surface geological data (field mapping, 1:10.000 scale) and the interpretation of a seismic reflection profile, kindly provided by Eni-Agip Division.

The section extends from the Umbra Valley Basin, west of Assisi, through the M. Subasio anticline, the Topino valley syncline and the «Inner Ridge» of the Umbria-Marche Apennines; the latter consists of seven box-shaped anticlines, with a wavelength of about 3 km. The seismic profile shows that at least the shallower part of the Basement is involved in the compressional structures, forming three steps stacked at depths ranging from 5 to 8 km, located between the M. Subasio anticline and the «Inner Ridge» of the Umbria-Marche Apennines. The interpreted section also allows a reconstruction of the deep geometry of the presumably active faults bounding the Colfiorito, Annifo and S.Martino basins.

These faults trend N140° $\pm$ 10°, dip towards SW at ~40°, to a depth of 8-9 km. The faults geometry is comparable with that suggested by the seismological data (focal mechanisms and aftershocks hypocenters) recorded during the 1997-98 seismic events. Seismicity seems to be confined above the top of the Basement: this lithological and mechanical discontinuity is suitable to be the base of the seismogenic layer in this region.

**KEY WORDS:** seismic profiles, geological sections, Basement depth, earthquakes.

## RIASSUNTO

**Integrazione di dati geologici e geofisici per la costruzione di un profilo attraverso l'area dell'Umbria-Marche (Italia) colpita dalla crisi sismica del 1997-98.**

Viene presentata una sezione geologica attraverso la regione Umbro-Marchigiana colpita dalla crisi sismica del 1997-98. La sezione, orientata circa N80° e passante circa 4 km a nord di Colfiorito, è il risultato di una integrazione tra dati di geologia di superficie e dati geofisici. In particolare è stato interpretato un profilo sismico a riflessione (gentilmente concesso da Eni-Agip Division) che attraversa l'area del terremoto, mentre i dati geologici provengono da recenti rilevamenti geologici di dettaglio (1:10.000) eseguiti dal Dipartimento di Scienze della Terra dell'Università di Perugia e promossi dalla Regione dell'Umbria. Il profilo mostra la geometria e la cinematica delle strutture rilevate in superficie e la loro estrapolazione in profondità. Tali geometrie possono essere confrontate con le profondità ipocentrali dei terremoti. Per tali eventi sono infatti disponibili numerosi dati strumentali, riguardanti le localizzazioni ipocentrali delle scosse principali e delle repliche, nonché i meccanismi focali (si veda ad es. AMATO *et alii*, 1998; BARBA & BASILI, 2000). In particolare per il terremoto di Colfiorito una rete locale ha consentito la registrazione di alcune migliaia di repliche, consentendone una localizzazione accurata (AMATO *et alii*, 1998).

Per quanto riguarda la tettonica compressiva, la sezione mette in evidenza il coinvolgimento del Basement, o almeno della sua porzione più superficiale, nella zona compresa tra il M. Subasio

e la Val Topina; le anticinali rilevabili in superficie sono invece relazionate a piani di scollamento più superficiali impostati nelle Evaporiti triassiche secondo uno stile a scollamenti sovrapposti già individuato nella interpretazione del profilo Crop03 (BARCHI *et alii*, 1998).

La tettonica distensiva si esprime attraverso faglie dirette a direzione prevalentemente appenninica (N140° $\pm$ 10°) con inclinazioni verso SW; è possibile individuare due gruppi: un gruppo occidentale che borda il bacino della Valle Umbra ed un gruppo più orientale che forma i bacini intramontani della catena (Colfiorito ed Annifo a nord, San Martino a sud) e che è stato attivato dalla crisi sismica del 1997-98 (si veda ad es. BASILI *et alii*, 1998; CELLO *et alii*, 1998; CALAMITA *et alii*, 1999).

Sulla base del dato sismico, le strutture estensionali sono scolate ad una profondità di circa 5-7 km in corrispondenza dei due piani complessivi principali che operano un raddoppio del Basement; tali strutture lasciano supporre che possano entrare nel Basement e sembrano invertire i thrusts almeno per piccoli settori.

Confrontando le geometrie evidenziate nella sezione presentata con i dati sulle profondità ipocentrali, che non superano i 9 km (AMATO *et alii*, 1998; BARBA & BASILI, 2000) è possibile supporre che il top del Basement costituisca la base dello strato sismogenetico.

**TERMINI CHIAVE:** profili sismici, sezioni geologiche, profondità del Basement, terremoti, ipocentri.

## INTRODUCTION

In this paper we present a geological cross-section (trace in fig. 1), which is the result of the interpretation of a seismic reflection profile (trace in fig. 1) integrated with surface geological data; the section is oriented about N80°, and crosses the Umbria-Marche Apennines (central Italy) about 4 km North of Colfiorito in the area where the 1997-98 seismic sequence occurred (fig. 1). The section permits the reconstruction of the possible depth geometry of the faults responsible for the 1997-98 Umbria-Marche earthquakes of the Colfiorito area and the analysis of their possible relationships with the inherited Miocene-Pliocene compressional tectonics.

As far as the surface data is concerned, the section was drawn on the base of 1:100.000 scale geological maps and it was enriched on the base of detailed surface data derived from 1:10.000 survey of the Colfiorito area.

The study area is located between the Umbra Valley Basin, west of Assisi and the «Inner Ridge» («Ruga Interna» of SCARSELLA, 1951; LAVECCHIA & PIALLI, 1980) of the Umbria-Marche Apennines, which is constituted of seven box-shaped anticlines, with a wavelength of about 3 km (LAVECCHIA *et alii*, 1988; TAVARNELLI, 1997).

These structures were formed during the Miocene-Pliocene compressional tectonic phase and were subsequently displaced by Quaternary normal faults related to the Pliocene-Quaternary extensional phase which started in the more western areas of the Apennines and moved in time and space from west to east (e.g. BARCHI *et alii*, 1998 and references therein). In particular, in the study area, the

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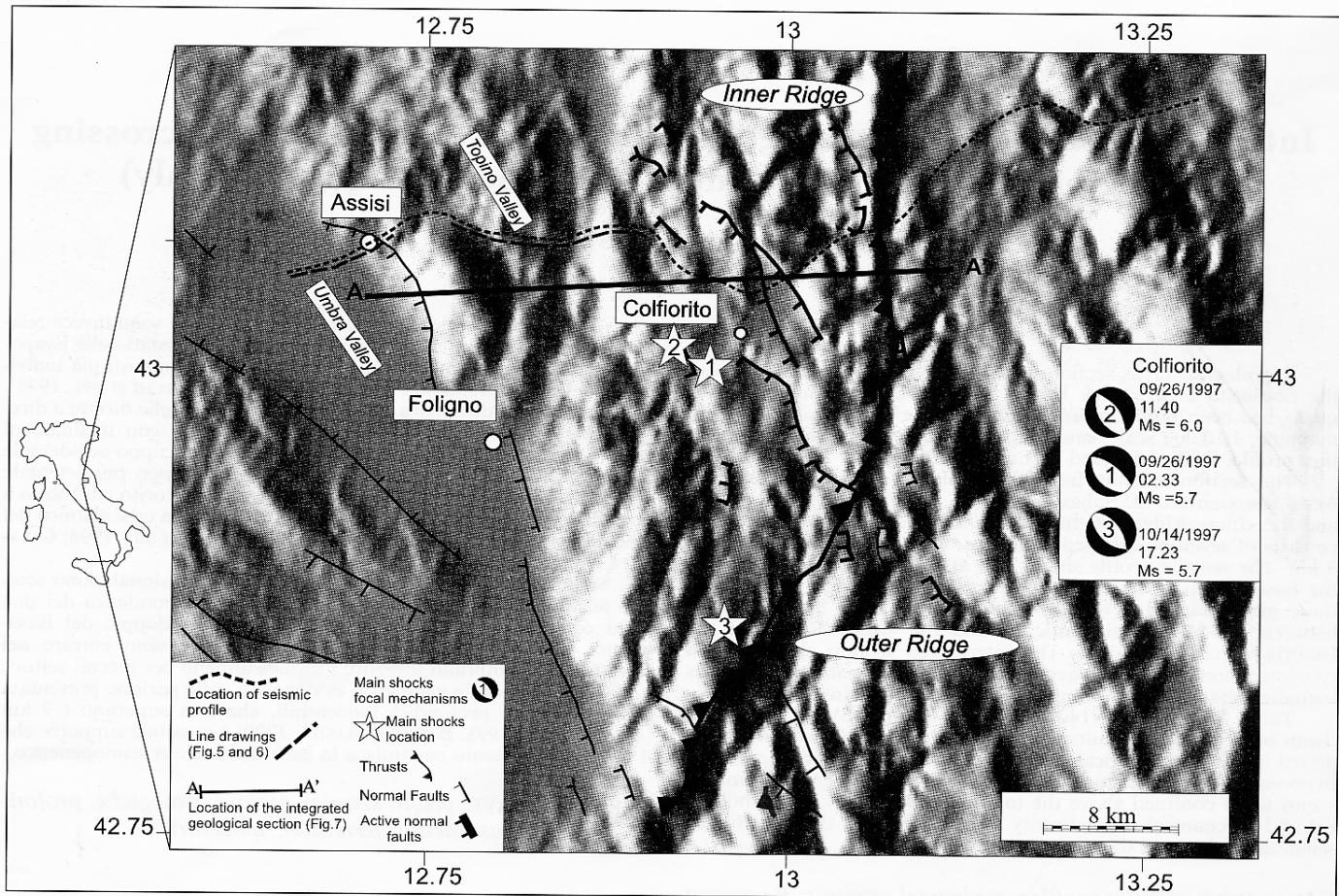


Fig. 1 - Schematic structural map, on shaded relief, of the study area with focal mechanisms (from EKSTRÖM *et alii*, 1998) of the main shocks of the Colfiorito seismic sequence.

- Carta strutturale schematica dell'area di studio con i meccanismi focali (da EKSTRÖM *et alii*, 1998) degli eventi principali della sequenza sismica di Colfiorito.

Quaternary normal faults form intramontane basins (Colfiorito and Annifo basins (fig. 2), San Martino basin, Verchiano basin). Fault kinematics of the Pliocene-Quaternary normal faults indicate an extensional stress field characterised by a  $\sigma_3$  oriented about NE-SW (BROZZETTI, 1995; BROZZETTI & LAVECCHIA, 1995; LAVECCHIA *et alii*, 1994; BONCIO & LAVECCHIA, 2000). Furthermore, historical seismicity ( $I_{MAX} = X$  MCS; Gruppo di Lavoro CPTI, 1999) and recent earthquakes (Norcia, 1979  $M = 5.9$ ; Gubbio, 1984  $M = 5.2$ ; Colfiorito, 1997-98  $M_{MAX} = 5.9$ ) indicate that this region is still experiencing extension and that seismicity is consistent with the active stress-field of the area obtained using both geological (LAVECCHIA *et alii*, 1994) and geophysical criteria (MARIUCCI *et alii*, 1999). In fact, instrumental data concerning the location of some last decades events, of the 1997-98 Colfiorito sequence (AMATO *et alii*, 1998; BARBA & BASILI, 2000) and the focal mechanisms (EKSTRÖM *et alii*, 1998) for the Colfiorito main shocks and aftershocks, show that the orientation of the present extensional stress field is about the same (NE-SW trending  $\sigma_3$ ) as that active since Pliocene (e.g. BONCIO *et alii*, 1996).

Information on the geometry of the active faults can be inferred by geological (surface mapping and boreholes) and geophysical data (seismic reflection profiles) which provide a reconstruction of the fault geometries at depth independent on the seismological information; these data have been

made available by the oil companies (ENI/AGIP in particular) since the middle of the 80's (e.g. BALLY *et alii*, 1986; SAGE *et alii*, 1991). The seismic reflection profiles though non-homogeneous for the acquisition methods, are a good tool in order to analyse the geometry of active faults to a depth of about 15 km; preliminary results have been already published for the Perugia-Gubbio area northern of Colfiorito (BARCHI *et alii*, 1999; PAUSELLI *et alii*, this Volume).

#### SURFACE GEOLOGY DATA

Concerning the surface geology, a detailed (1:10.000 scale) field mapping of the area struck by the Colfiorito earthquake has been performed by the Dipartimento di Scienze della Terra Università di Perugia, in co-operation with Regione Umbria (Servizio Geologico). On the basis of the 1:10.000 maps, a structural sketch (fig. 3) and some geological cross-sections were drawn, one of which (fig. 4a) was chosen in order to give a good surface constrain to the seismic profile.

#### STRATIGRAPHY AND SYNSEDIMENTARY TECTONICS

The surface mapping area comprehends the region between M. Di Lello and M. Le Scalette-M. Prefoglio (figs.

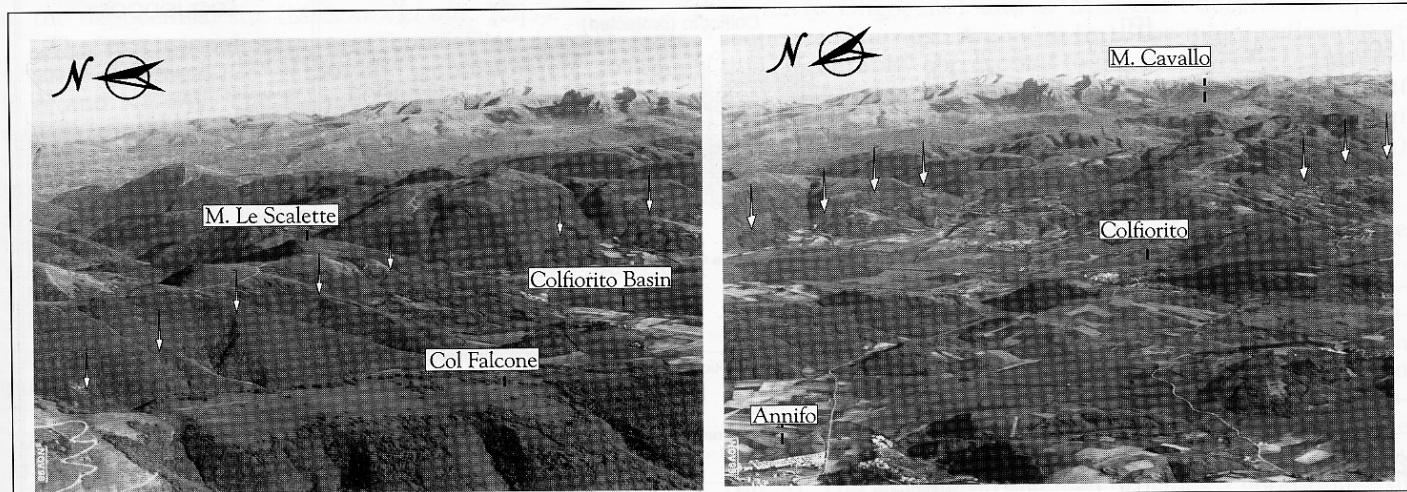


Fig. 2 - Views of M. Le Scalette, M. Prefoglio normal faults (arrows point to fault locations) located in the Colfiorito area.  
– Panorama sulle faglie dirette (le frecce indicano l'ubicazione delle faglie) di M. Le Scalette, M. Prefoglio nell'area di Colfiorito.

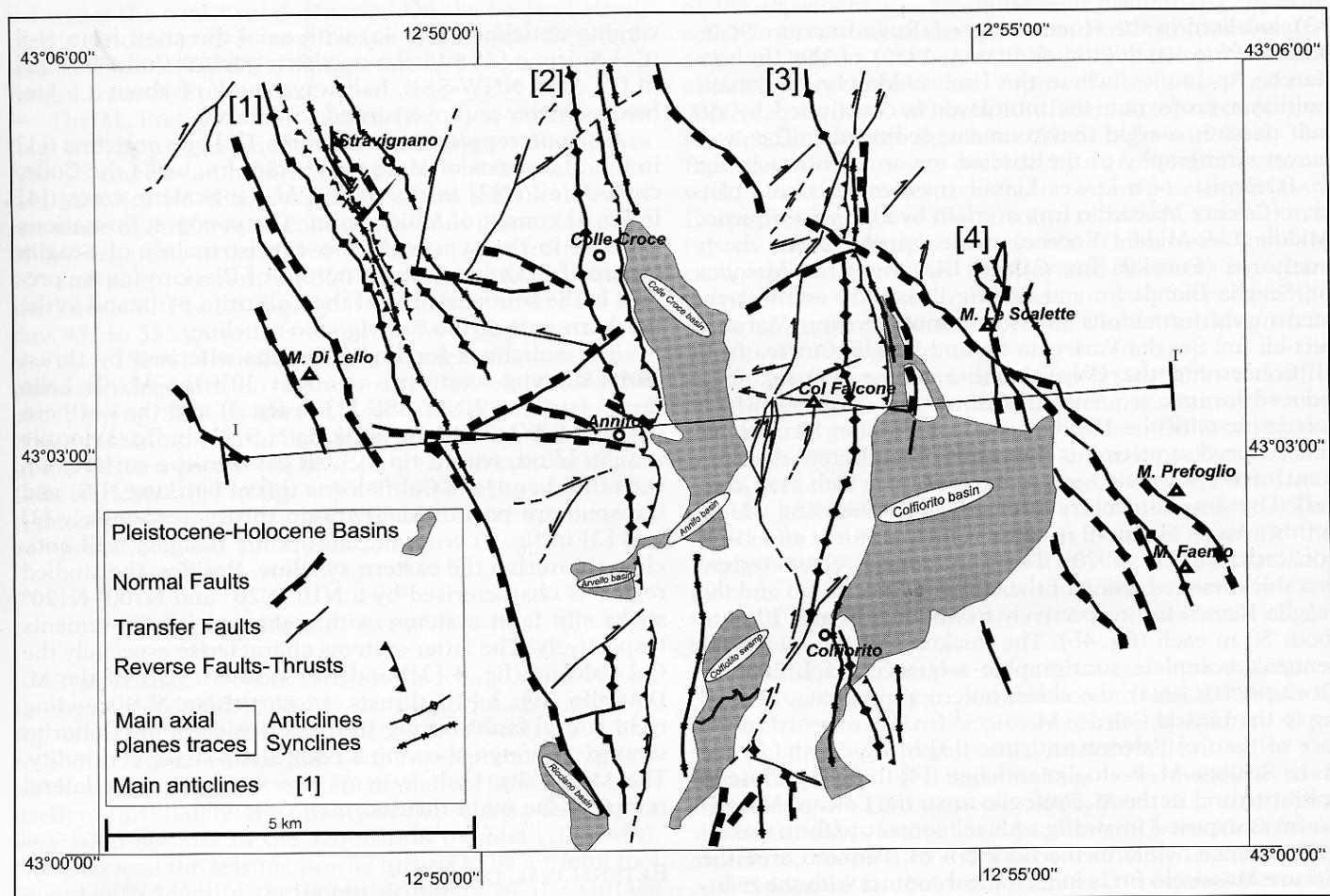


Fig. 3 - Sketch of the detailed tectonic features mapped north of the Colfiorito area and trace of geological section of fig. 4.  
– Localizzazione delle strutture tettoniche rilevate nell'area a nord di Colfiorito e traccia della sezione geologica di fig. 4.

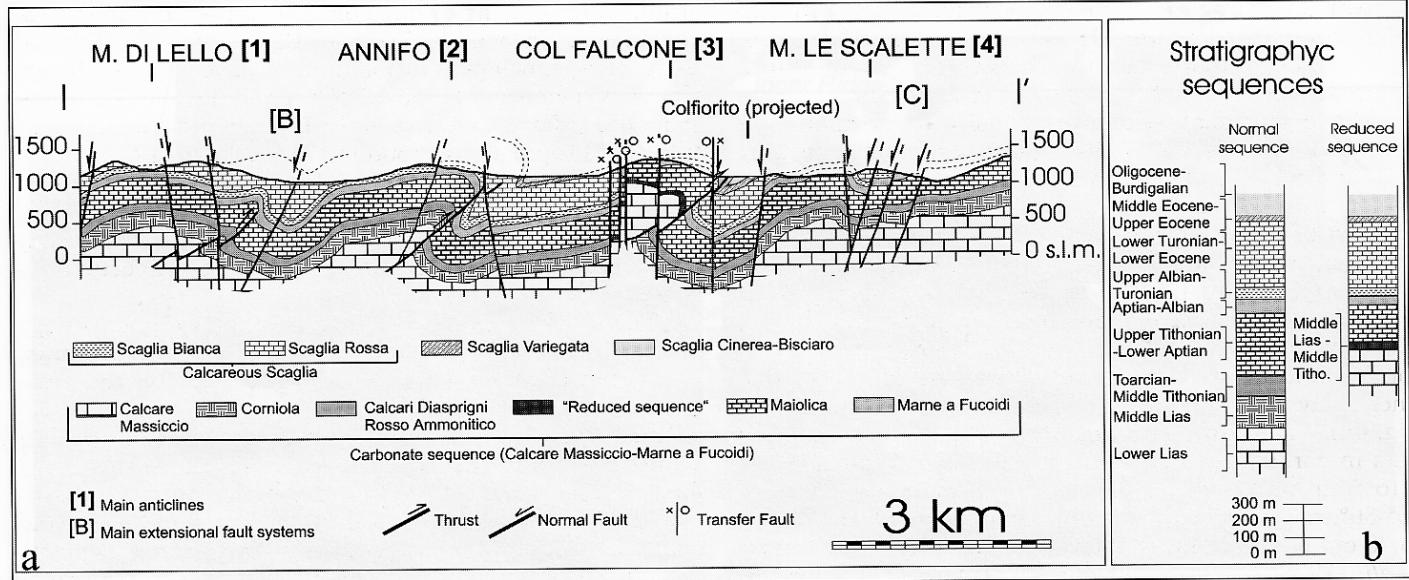


Fig. 4 - Geological cross-section (a) (trace in fig. 3) derived from detailed surface field-work and related stratigraphy (b).  
- Sezione geologica (a) (la cui traccia è riportata in fig. 3) derivata dal rilevamento geologico di dettaglio e relativa stratigrafia (b).

2-3), localised in the «Inner Ridge» («Ruga Interna» SCARSELLA, 1951; LAVECCHIA & PIALLI, 1980) of the Umbria-Marche Apennines, where the Umbria-Marche carbonatic multilayer crops out; the multilayer is constituted by rift and passive margin environment sediments. The well known stratigraphy of the studied region is shown in fig. 4b. It consists of a Lower Liassic massive carbonate platform (Calcare Massiccio fm), overlain by a pelagic sequence (Middle Lias-Middle Eocene) made up of basinal cherty limestones (Corniola fm, Calcari Diasprigni fm, Maiolica fm, Scaglia Bianca fm and Scaglia Rossa fm) and intercalated marly formations (Rosso Ammonitico fm, Marne a Fucoidi fm, Scaglia Variegata fm and Scaglia Cinerea fm).

Concerning the Col Falcone anticline ([3] fig. 3) a reduced Jurassic sequence (Bugarone fm) crops out which is eteropic with the Middle Lias to Tithonian formations. This reduced sequence, is the result of a different development of the Jurassic sedimentary basin which was controlled by sin-sedimentary extensional tectonics and which, in this area, is about 40 m thick (CENTAMORE *et alii*, 1971; COLACICCHI *et alii*, 1970). The same area is characterised by a thickness reduction of the Marne a Fucoidi fm and the Scaglia Bianca fm, respectively from 80-90 m and 70 m to about 50 m each (fig. 4b). The thickness of the Mesozoic-Cenozoic complete stratigraphic sequence reach 2000 m (COLACICCHI, 1994); the eldest outcropping strata, belonging to the Liassic Calcare Massiccio fm, are exposed in the core of the Col Falcone anticline ([3] in fig. 3) and in the M. Le Scalette-M. Prefoglio anticline ([4] in fig. 3). Close to Colfiorito and in the M. Prefoglio area, the Calcare Massiccio fm is exposed in stratigraphical contact with the reduced sequence, while in the northern M. Pennino area the Calcare Massiccio fm is in tectonical contact with the reduced sequence by means of Jurassic normal faults.

#### COMPRESSIVE TECTONICS

The compressional tectonics of the surveyed area, expresses through a set of four main asymmetrical east-

verging anticlines (fig. 4a) with axial direction from N-S (Col Falcone [3] and the northern part of Collecroce [2] in fig. 3) to NNW-SSE, half-wavelength of about 1.5 km, box geometry and overturned forelimbs.

The outcropping core of the M. Di Lello anticline ([1] in fig. 3) consists of Marne a Fucoidi fm, while the Collecroce-Annifo ([2] in fig. 3) and M. Le Scalette cores ([4] in fig. 3) consist of Maiolica fm. The youngest formations exposed in the synclines core consist mainly of Scaglia Cinerea fm. Only smaller outcrops of Bisciari fm are present in the southern area of the Colfiorito plain and in the northern part of the Stravignano syncline.

The anticlines forelimbs are characterised by thrust faults dipping westward of about 30°; the M. Di Lello thrust (striking NNW-SSE [1] in fig. 3) and the northern part of M. D'Annifo one (striking N-S, [2] in fig. 3) locally remain blind, with a tip located close to the surface. On the other hand, the Col Falcone thrust (striking N-S) and the southern part of M. D'Annifo thrust (respectively [3] and [2] in fig. 3) crop out and let the hanging wall anticline to overlap the eastern syncline. Besides, the studied region is characterised by a N10°-N20° and N100°-N120° strike slip fault systems, with right and left movements respectively. The latter systems characterise especially the Col Falcone (fig. 3 [3]) and the southern part of the M. D'Annifo (fig. 3 [2]) thrusts. In particular, N-S trending right lateral faults border the eastern side of the Colfiorito swamp, although showing a poor along-strike continuity. The strike slip fault systems are interpreted as lateral ramps of the main thrusts.

#### EXTENSIONAL TECTONICS

In this area of the Apennines, the principal basins are located in correspondence with synclines and some of them (Riccianno basin) are depressions bounded by Pleistocene-presently active normal faults.

These basins (intramontane basins) are infilled with Pleistocene-Holocene deposits (COLTORTI *et alii*, 1998;

FICCARELLI & MAZZA, 1990). In particular the Colfiorito basin consists of Lower-Middle Pleistocene fluvio-lacustrine deposits, that reach the thickness of about 120 m in the depocentral site (MESSINA *et alii*, 1999).

The extensional structures consist of normal fault systems striking N125°-N150° and, subordinately, striking E-W and NE-SW. The former, the most important fault system, dips 45° to 70° towards SW and bounds the eastern part of the Colfiorito basin (fig. 3). It consists of two principal arrays: M. Le Scalette and M. Prefoglio fault systems ([C] in fig. 4). The M. Le Scalette fault (fig. 2) is constituted by segments organised in sub-parallel sets, the strike of which ranges from N110° to N160°; along its southernmost part it is possible to single out three distinct splays that show a total displacement up to 200 m (fig. 4a). The most continuous fault plane (M. Le Scalette) puts in contact the debris cover with the Maiolica fm, is 2 to 8 m high and, on the base of slickensides rakes of 70°-80°, reveals a slight left oblique movement. Besides, 2 to 20 cm high free-faces, which some authors (e.g. CELLO *et alii*, 1998; CALAMITA *et alii*, 1999) consider a feature due to co-seismic reactivation during the 1997 earthquake, are locally exposed. Another normal fault is located in the western part of the M. Le Scalette limb; this fault plane is not visible and it is almost completely buried under the continental deposits. On the basis of stratigraphic evidence, it is possible to assert that this fault strikes about NNW-SSE, dips toward WSW and its throw ranges from 200 to 400 m.

The M. Prefoglio fault system (fig. 3) is organised in four SW dipping segments: the westernmost one strikes NW-SE and has an hidden fault plane which puts in contact Maiolica fm with Scaglia Rossa fm with a throw of not more than 200 m. A continuous fault plane, eastward of this segment, strikes N130° to N150°, dips from 60° to 70° and its throw reaches 300 m. Another fault plane is sited near M. Faento (fig. 3): it constantly strikes N130°, dips 45° to 55° towards SW and shows a displacement of less than 150 m. The easternmost segment displays a fault plane striking with an average direction of N150°+20° and dipping 55°. Its throw is of ~200-300 m. Another N130°-N150° normal fault system ([B] in fig. 4a) is sited in the western part of the studied area and cuts the M. Di Lello anticline ([1] in fig. 4a) with a set of synthetic and right-stepping segments. The throw of these segments is comprised between 100m and 200 m.

#### SEISMIC DATA

The seismic section crosses the chain from Assisi, through the Topino Valley, to the Colfiorito area (trace in fig. 1) and reaches the depth of 5 s (twt), corresponding to about 12 km. To the aim of the interpretation, both a stack and a migrated version of the section have been used; unfortunately, the quality of the seismic data is not very good because of the acquisition method (vibroseis). Nevertheless, the seismic profile turned to be a useful tool in order to identify the depth geometry of the surface structures. The seismic interpretation was based on a preliminary line-drawing of the main reflectors to which were subsequently assigned some formations of the Umbria-Marche stratigraphy.

To the purpose of the seismic interpretation, it is possible to schematically divide the Umbria-Marche stratigraphy

into four lithological units: from bottom to top we consider a Palaeozoic-Triassic Basement *s.l.*, Triassic Evaporites, a pelagic Carbonate multilayer (Lower Jurassic-Early Oligocene) and a Miocene-Pliocene Turbidite sequence (Marnoso Arenacea fm). The major reflectors of this stratigraphy correspond to the Basement *s.l.*- Evaporites boundary, to the marly Marne a Fucoidi (Aptian-Albian) fm and to the boundary between the Bisciaro fm (Early Miocene) and the marly Schlier (Middle Miocene) which precedes the Marnoso Arenacea fm (Miocene-Pliocene).

The stack version of the profile shows a good image of the Umbra Valley basin and its related normal faults, to a depth of about 1.5 s (twt). Figure 5 shows the presence of a main W-dipping normal fault which corresponds, at surface, to the boundary between the Umbra Valley Basin and the M. Subasio anticline. To this main fault, a set of synthetic and antithetic faults are associated. They displace the reflector corresponding to the base of the continental Pliocene(?) -Quaternary deposits (fig. 5). The seismic profile also provides a good image of the structures present beneath the M. Subasio anticline and Topino Valley to a depth of about 3.5 s (twt) (fig. 6). The reflections within the carbonates underlying the Marnoso Arenacea fm and the reflector interpreted as the top of the Basement *s.l.*, are quite well evident (fig. 6). The reflections related to the top of the Basement are located at about 2-2.5 s (twt) beneath the M. Subasio anticline, at about 3 s (twt) under the Topino Valley and at greater depth (about 3.5 s twt) beneath the area corresponding to the first anticline of the chain (M. di Lello anticline). The Basement reflectors are overlaid by a group of reflections, with a light character, which correspond to the Triassic Evaporites fm; above them, some reflectors, corresponding to the carbonates are visible. These reflectors are quite well evident under the Marnoso Arenacea fm, characterised by a good «transparency» with respect to the seismic waves, while are not well visible in those areas where the carbonates crop out. In fact, as far as the «chain area» is concerned, the depth structures are difficult to be interpreted without a good constraint given by the surface geology. Nevertheless, the reflections of the top of the Basement are strong enough even under the chain area and provide an important constraint for drawing the geometry of the surface structures at depth. The reflections of the top of the carbonates beneath the Topino Valley show a synform; the carbonates dip towards the east and towards the west respectively eastward of the M. Subasio anticline and westward of the chain.

On the basis of the seismic images and through a depth conversion, it is possible to estimate the depth of the Basement under this portion of the Apennines. Concerning the depth conversion, interval velocities for the different groups of reflectors have been mostly derived from literature (BALLY *et alii*, 1986; BARCHI *et alii*, 1998): the Basement is located at 5.5 km beneath the M. Subasio structure, deepens to 8.0 km beneath the Topino Valley and is located at about 8.5-9 km in correspondence with the first anticline of the chain (M. Di Lello anticline). Furthermore, the seismic section shows west dipping reflections, displacing the Basement (fig. 6). In our opinion, on the base of this data it is possible to assert that the Basement is involved in the compressional deformation, giving rise to at least two steps (fig. 6).

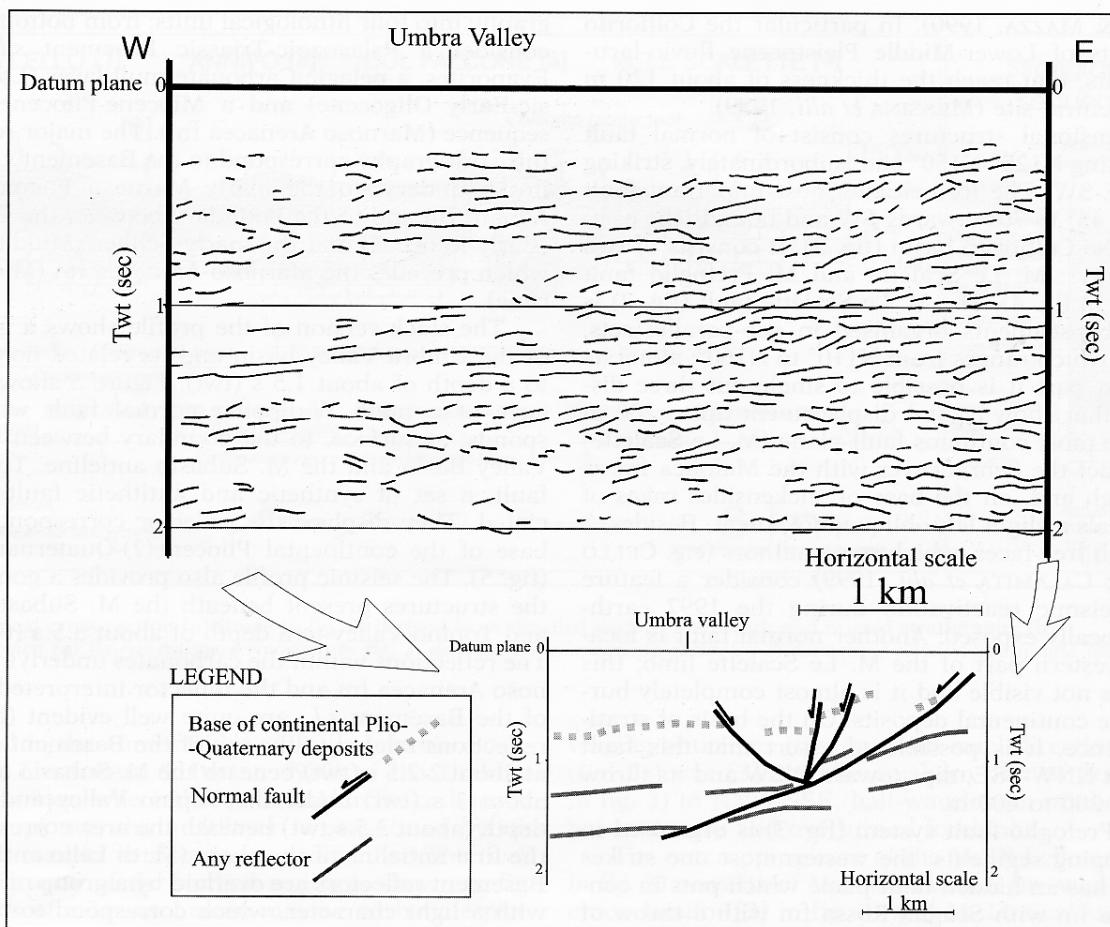


Fig. 5 - Line drawing of a seismic image of the Umbra Valley Basin and its related normal faults (trace in fig. 1).  
- Immagine sismica del bacino della Valle Umbra e delle relative faglie dirette (traccia in fig. 1).

#### AN INTEGRATED GEOLOGICAL SECTION

Fig. 7 is a geological section drawn from the Umbra Valley basin across the «Inner Ridge», to a depth of 9 km; the section is the result of the integration of surface geological data with seismic data. In particular the surface geological cross section of fig. 4a coincides with the central part of the section of fig. 7.

The integration of surface data with seismic sections allows to draw the surface data, inferred from survey, to depth and to make some geometric and kinematic considerations in order to compare the geometries of the faults with the seismological data (e.g. hypocenters distribution, focal mechanisms).

#### DESCRIPTION OF THE INTEGRATED GEOLOGICAL SECTION

In fig. 7, from west to east the compressional tectonics is evidenced by the M. Subasio anticline, by the «Inner Ridge» anticlinorium and by the two main thrusts of the «Inner Ridge» (M. Di Massa and Pieve Bovigliana thrusts). The section presented shows that in this area the M. Subasio thrust involves a small Basement scale and that the «Inner Ridge» thrusts, the importance of which is mainly suggested by regional geology for the great longitudinal continuity, are characterised by the major throw and involve the Basement, forming at least two steps loc-

alised under the M. Subasio anticline and the Topino Valley (fig. 6); on the other hand, the group of anticlines characterised by a shorter wavelength (about 3 km) are detached on the Triassic Evaporites level in accordance with the «multiple detachment» model (BARCHI *et alii*, 1998), which testifies of apparent disarray between the throw of the thrusts at depth and their throw at surface. The thrust corresponding to the higher step of the Basement is the thrust at the hanging wall of which the group of the «Inner Ridge» anticlines are localised. The second step corresponding thrust (Pieve Bovigliana thrust), is the thrust which separates the «Inner Ridge» by the «Outer Ridge» («Ruga Interna e Ruga Esterna» of SCARSELLA, 1951) of the belt.

Along the section, the main extensional structures are the faults bounding the Umbra Valley Basin (see fig. 5 and [A] in fig. 7), the faults which concern the M. Di Lello anticline ([B] in figs. 4-7) and the faults which concern the M. Le Scalette and M. Prefoglio anticlines ([C] in figs. 4-7) eastward of the Colfiorito basins. The main faults of the M. Di Lello anticline, dipping to the SW with an inclination of ~60° at surface and ~40° at depths of ~2.5-3.5 km, seem to invert a segment of the Col Falcone thrust ([3] in fig. 3). The total throw of these two synthetic faults is up to 600 m. At the hanging wall, two small east dipping antithetic segments are also present. On the basis on the seismological data (AMATO *et alii*, 1998; BARBA &

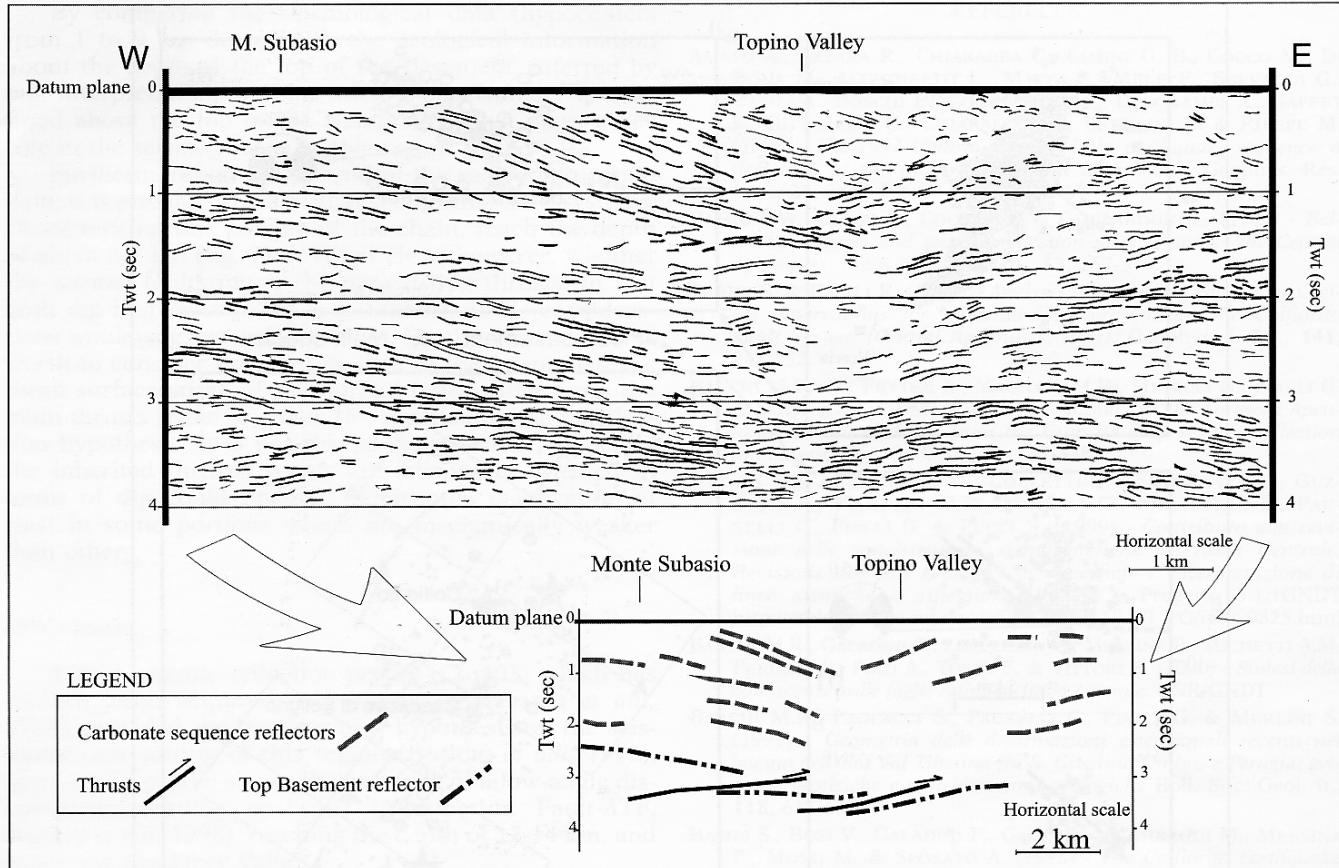


Fig. 6 - Line drawing of a seismic image of the Basement reflectors beneath M. Subasio and Topino Valley (trace in fig. 1).  
- Immagine sismica dei riflettori del Basamento al di sotto del M. Subasio e della Valle del Topino (traccia in fig. 1).

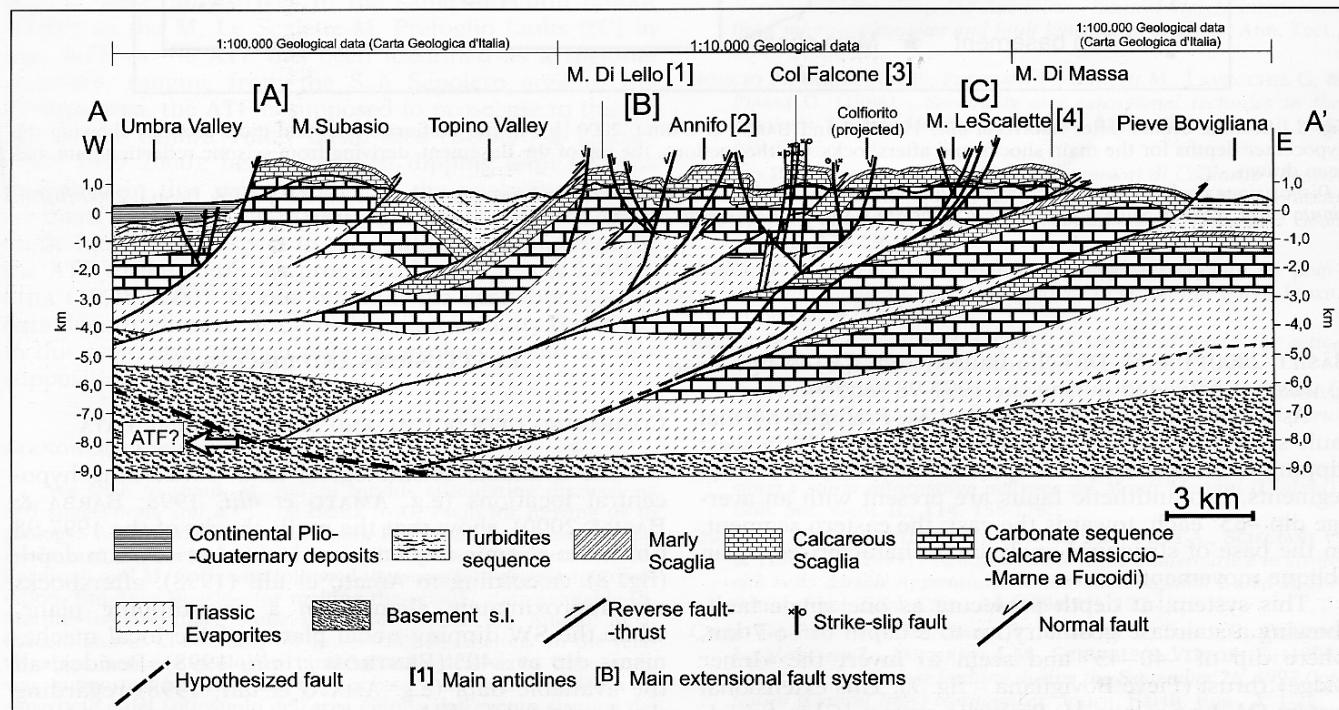


Fig. 7 - Integrated geological section across the 1997-98 Umbria-Marche earthquake area (Trace in fig. 1).  
- Sezione geologica integrata attraverso l'area Umbro-Marchigiana colpita dal terremoto del 1997-98. (Traccia in fig. 1).

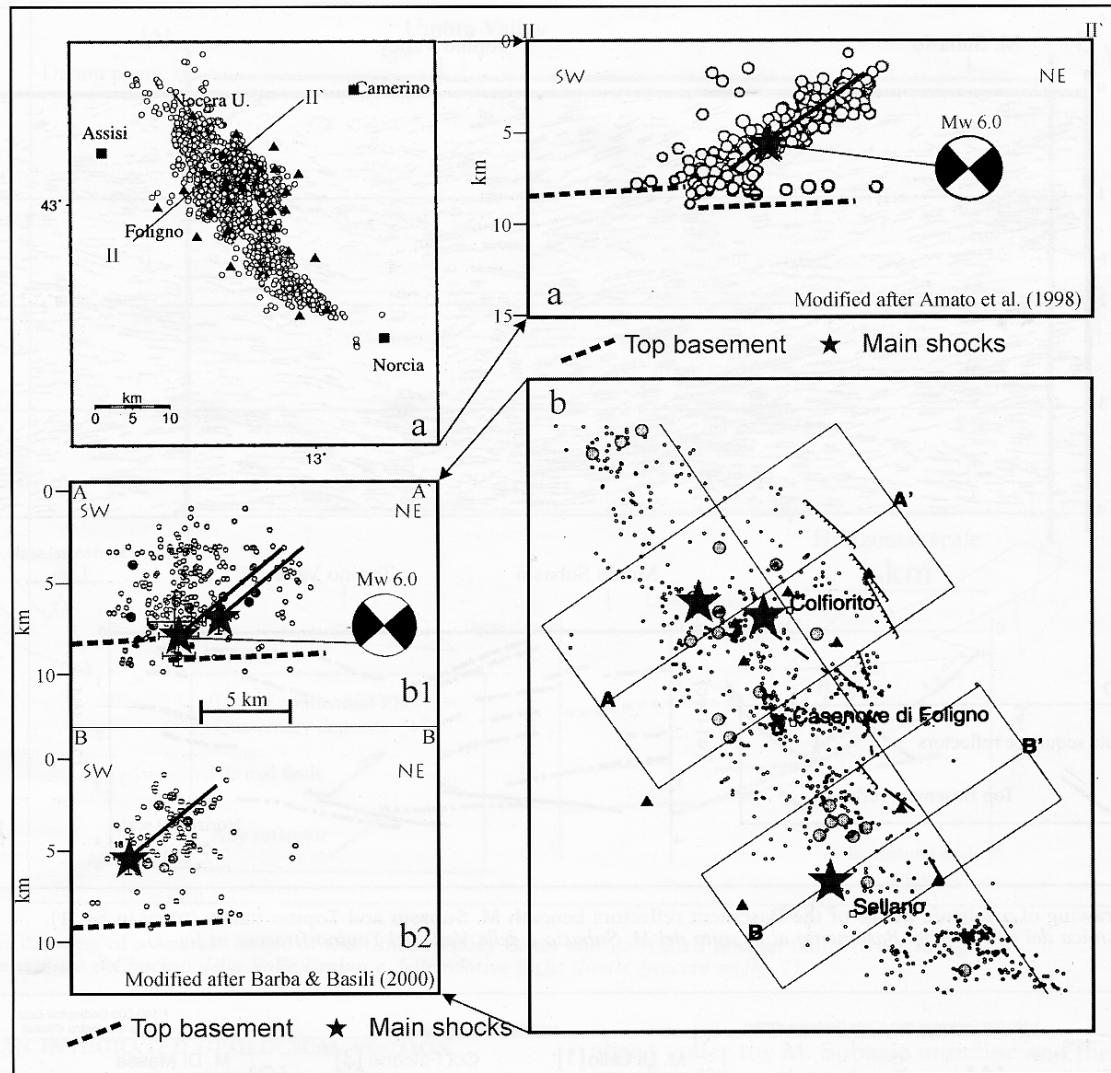


Fig. 8 - Seismic events (after AMATO *et alii*, 1998 [a] and BARBA & BASILI, 2000 [b]) in the Colfiorito area and cross-sections showing the hypocenter depths for the main shocks and aftershocks. On the sections, the top of the Basement, deriving from seismic reflection data, has been drawn.

- Disposizione degli eventi sismici principali e delle repliche nell'area di Colfiorito (da AMATO *et alii*, 1998 [a] e BARBA & BASILI, 2000 [b]) in pianta ed in sezione. Sulle sezioni è stato riportato il top del Basement derivato dai profili sismici a riflessione.

BASILI, 2000) the M. Di Lello fault system ([B] in figs. 4-7) was not activated during the 1997-98 sequence.

As far as the M. Le Scalette and M. Prefoglio normal fault system is concerned, it is formed by a main west dipping fault, which show dips  $\sim 60^\circ$  at surface; to these segments, two antithetic faults are present with an average dip  $\sim 65^\circ$  each, towards the east: the eastern segment, on the base of structural analysis, is characterised by an oblique movement.

This system, at depth prosecute as one single fault, showing a staircase geometry up to a depth of  $\sim 6$ -7 km, where dip of  $\sim 40$ - $45^\circ$  and seem to invert the «Inner Ridge» thrust (Pieve Bovigliana - fig. 7). This extensional system (M. Le Scalette-M. Prefoglio system [C] in figs. 4-7) was activated during the 1997-98 earthquakes (BASILI *et alii*, 1998).

## CONCLUSIONS AND DISCUSSION

### COMPARING GEOLOGICAL AND SEISMOLOGICAL DATA

The available seismological data, concerning hypocentral locations (e.g. AMATO *et alii*, 1998; BARBA & BASILI, 2000), show that the main shocks of the 1997-98 Colfiorito seismic sequence are located at  $\sim 6$ -7 km depth (fig. 8). According to Amato *et alii* (1998), aftershocks are approximately aligned on a west-dipping plane, while the SW dipping nodal planes of the focal mechanisms dip at  $\sim 40^\circ$  (EKSTRÖM *et alii*, 1998). Besides, all the available data (e.g. AMATO *et alii*, 1998) regarding the depth of the whole seismic sequence, put in evidence that the hypocenters depths are confined in the shallower 9 km.

By comparing the seismological data (hypocenters from 1 to 9 km deep), with the geological information about the depth of the top of the Basement, inferred by our interpretation, we can infer that seismicity is confined above the top of the Basement which plays a key role in the seismogenesis in this region.

Furthermore, on the ground of the seismic reflection data, it is possible to assert that the normal fault systems, characterising this portion of the chain, reach the depth of about 6-7 km (fig. 7). It is not clear, however, whether the normal faults invert the pre-existing thrusts: in fact both dip and mechanical (e.g. SIBSON, 1985) considerations would suggest a reactivation. On the other side, it is worth to consider that, in this area of the Apennines, the mean surface strike of the normal faults differ from the main thrusts strike of about 35°, contrasting the reactivation hypothesis. It is possible to suppose that, at depth, the inherited thrusts, which are favourably oriented in terms of dip could undergo extensional reactivation at least in some portions which are mechanically weaker than others.

## DISCUSSION

A deep seismic reflection profile (Crop03) which has recently been acquired and interpreted (PIALLI *et alii*, 1998), provided the base for new hypothesis on the seismotectonic setting of this region (BONCIO *et alii*, 1998). The Crop03 profile shows the presence of a low-angle discontinuity dipping eastward (Altotiberina Fault-ATF, BARCHI *et alii*, 1998), reaching the depth of 13-14 km, and bordering the Tiber Valley.

Northern of Colfiorito, the seismogenic Gubbio fault (LAVECCCHIA *et alii*, 1994; BONCIO *et alii*, 1998; BARCHI *et alii*, 1999; BARCHI *et alii*, 2000) is antithetic to the ATF, dips to west, and strikes in the same direction (about N130°) as the M. Le Scalette-M. Prefoglio faults ([C] in figs. 4-7); as the ATF has been identified as a regional structure, ranging from the San Sepolcro area to the Perugia area, the ATF is supposed to prosecute to the SE also in the Umbra Valley Basin area (BONCIO & LAVECCCHIA, 1999 2000); hence the west dipping fault systems described in this paper would be the analogous of the northern Gubbio fault in this area and would be antithetic faults with respect to the southern continuation of the ATF to the south, as proposed by BONCIO & LAVECCCHIA (1999, 2000). In our opinion, the available seismic data doesn't allow to draw such a discontinuity (i.e. ATF) in this area, even though regional geology would let this supposition be reasonable.

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## REFERENCES

- AMATO A., AZZARA R., CHIARABBA C., CIMINI G. B., COCCO M., DI BONA M., MARGHERITI L., MAZZA S., MELE F., SELVAGGI G., BASILI A., BOSCHI E., COURBOULEX F., DESCHAMPS A., GAFFET S., BITTARELLI G., CHIARALUCE L., PICCININI D. & RIPEPE M. (1998) - *The 1997 Umbria-Marche, Italy, earthquake sequence: a first look at the main shocks and aftershocks*. Geophys. Res. Lett., **25**, 2861-2864.
- BALLY A.W., BURBI L., COOPER C. & GHELARDONI L. (1986) - *Balanced sections and seismic reflection profiles across the Central Apennines*. Mem. Soc. Geol. It., **35**, 257-310.
- BARBA S. & BASILI R. (2000) - *Analysis of seismological and geological observations for moderate-size earthquakes: the Colfiorito Fault System (Central Apennines, Italy)*. Geophys. J. Int., **141**, 241-252.
- BARCHI M.R., DE FEYTER A., MAGNANI M.B., MINELLI G., PIALLI G. & SOTERA M. (1998) - *Extensional tectonics in the northern Apennines (Italy): evidence from the Crop 03 deep seismic reflection line*. Mem. Soc. Geol. It., **52**, 527-538.
- BARCHI M.R., CARDINALI M., COLLETTINI C., COSTANZO F., GUZZETTI F., MAGNANI M.B., MINELLI G., MIRABELLA F., PAUSSELLI C., PIALLI G. & PUCCI S. (1999) - *Contributo alla revisione delle zone/strutture sismogenetiche dell'Italia Centrale. Revisione dei dati geologici di superficie e interpretazione di linee sismiche a riflessione*. PE 98 - Progetto 5.1.1GNDT [http://emidius.itim.mi.cnr.it/GNDT/P511/UNI\\_PG/rel990825.html](http://emidius.itim.mi.cnr.it/GNDT/P511/UNI_PG/rel990825.html)
- BARCHI M.R., GALADINI F., LAVECCCHIA G., MESSINA P., MICHETTI A.M., PERUZZA L., PIZZI A., TONDI E. & VITTORI E. (2000) - *Sintesi delle conoscenze sulle faglie attive in Italia centrale*. CNR-GNDT.
- BARCHI M.R., PAOLACCI S., PAUSSELLI C., PIALLI G. & MERLINI S. (1999) - *Geometria delle deformazioni estensionali recenti nel bacino dell'alta Val Tiberina fra S. Giustino Umbro e Perugia: evidenze geofisiche e considerazioni geologiche*. Boll. Soc. Geol. It., **118**, 617-625.
- BASILI S., BOSI V., GALADINI F., GALLI P., MEGHRAOUI M., MESSINA P., MORO M. & SPOSATO A. (1998) - *The Colfiorito earthquake sequence of September-October 1997: surface breaks and seismotectonic implications for the central Apennines (Italy)*. Journ. Earth. Eng., **2**, 291-302.
- BONCIO P., BROZZETTI F. & LAVECCCHIA G. (1996) - *State of stress in Northern Umbria-Marche Apennines (central Italy): interferences from microearthquakes and fault kinematics analysis*. Ann. Tect., **10** (1-2), 80-97.
- BONCIO P., BROZZETTI F., PONZIANI F., BARCHI M., LAVECCCHIA G. & PIALLI G. (1998) - *Seismicity and extensional tectonics in the Northern Umbria-Marche Apennines*. Mem. Soc. Geol. It., **58**, 539-555.
- BONCIO P. & LAVECCCHIA G. (1999) - *I terremoti di Colfiorito (Appennino umbro-marchigiano) del Settembre-Ottobre 1997: contesto tettonico e prime considerazioni sismogenetiche*. Boll. Soc. Geol. It., **118**, 229-236.
- BONCIO P. & LAVECCCHIA G. (2000) - *A geological model for the Colfiorito earthquakes (September-October 1997, central Italy)*. Journ. of Seism., **4** (4), 345-356.
- BONCIO P. & LAVECCCHIA G. (2000) - *A structural model for active extension in Central Italy*. Journ. of Geod., **29**, 233-244.
- BROZZETTI F. (1995) - *Stile strutturale della tettonica distensiva nell'Umbria occidentale: l'esempio dei Massicci Mesozoici Perugini*. Stud. Geol. Cam., vol. spec. 1995/**1**, 105-119.
- BROZZETTI F. & LAVECCCHIA G. (1995) - *Evoluzione del campo degli sforzi e storia deformativa nell'area dei Monti Martani (Umbria)*. Boll. Soc. Geol. It., **114**, 155-176.
- CALAMITA F., COLTORTI M., PIERANTONI P.P., PIZZI A., SCISCIANI V. & TURCO E. (1999) - *Relazioni tra le faglie quaternarie e la sismicità nella dorsale Appenninica umbro-marchigiana: L'area di Colfiorito*. Stud. Geol. Cam., **14** (1996-97), 177-191.
- CELLO G., DEIANA G., MANGANO P., MAZZOLI S., TONDI E., FERRELLI L., MASCHIO L., MICHETTI A.M., SERVA L. & VITTORI E. (1998) - *Evidence for surface faulting during the September 26, 1997 Colfiorito (Central Italy) earthquakes*. Journ. Earth. Eng., **2**, 1-22.
- CENTAMORE E., CHIOCCHINI M., DEIANA G., MICARELLI A. & PIERRUCCINI U. (1971) - *Un contributo alla conoscenza del Giurassico dell'Appennino Umbro-Marchigiano*. Stud. Geol. Cam., **1**, 7-89.

- COLACICCHI R., PASSERI L. & PIAZZI G. (1970) - Nuovi dati sul Giurassico Umbro-Marchigiano ed ipotesi per un suo inquadramento regionale. Mem. Soc. Geol. It., **9**, 839-874.
- COLACICCHI R. (1994) - Le successioni pelagiche del Giurassico in: PASSERI L. (1994) - 15 Itinerari - Appennino Umbro-Marchigiano Guide Geologiche Regionali, Soc. Geol. It., **7**, 27-31, BE-MA Editrice (Lodi-Milano).
- COLTORTI M., ALBIANELLI A., BERTINI A., FICCARELLI G., LAURENZI M., NAPOLEONE G. & TORRE D. (1998) - The Colle Curti mammal site in the Colfiorito area (Umbro-Marchean Apennine, Italy): Geomorphology, stratigraphy, paleomagnetism and palynology. Quat. Int., **47**(8), 107-116.
- EKSTRÖM G., MORELLI A., BOSCHI E. & DZIEWONSKI A.M. (1998) - Moment tensor analysis of the central Italy earthquake sequence of September-October 1997. Geophys. Res. Lett., **25**, 1971-1974.
- FICCARELLI G. & MAZZA P. (1990) - New fossil findings from the Colfiorito basin (Umbro-Marchean Apennine). Boll. Soc. Pal. It., **29**(2), 245-247.
- GRUPPO DI LAVORO CPTI (1999) - Catalogo parametrico dei terremoti italiani. ING, GNDT, SGA, SSN, Bologna, 92 pp.
- LAVECCHIA G. & PIAZZI G. (1980) - Appunti per uno schema strutturale dell'appennino Umbro Marchigiano. 2) La copertura St. Geol. Cam., **6** (23-30).
- LAVECCHIA G., BARCHI M.R., BROZZETTI F. & MENICHETTI M. (1994) - Sismicità e tettonica nell'area Umbro-Marchigiana. Boll. Soc. Geol. It., **113** (483-500), 10 ff.
- LAVECCHIA G., BROZZETTI F., BARCHI M.R., KELLER J. & MENICHETTI M. (1994) - Seismotectonic zoning in east-central Italy deduced from the analysis of the Neogene to present deformation and related stress fields. Geol. Soc. Am. Bull., **106**, 1107-1120.
- LAVECCHIA G., MINELLI G. & PIAZZI G. (1988) - The Umbria Marche arcuate Fold Belt (Italy). Tectonophysics, **146**, 125-137.
- MARIUCCI M.T., AMATO A. & MONTONE P. (1999) - Recent tectonic evolution and present stress in the Northern Apennines. Tectonics, **18**, 108-118.
- MESSINA P., GALADINI F., GALLI P. & SPOSATO A. (1999) - Evoluzione a lungo termine e caratteristiche della tettonica attiva nell'area Umbro-Marchigiana colpita dalla sequenza sismica del 1997-98 (Italia Centrale). In «Progetto MISHA - Metodi innovativi per la stima dell'hazard: applicazione all'Italia centrale»; (a cura di L. Peruzzi), CNR-Gruppo Nazionale per la Difesa dei Terremoti, Roma, pp. 32-42.
- PAUSELLI C., MARCHESI R. & BARCHI M. (2000) - Seismic image of the compressional and extensional structures in the gubbio area (umbrian-pre apennines). This Volume.
- PIAZZI G., BARCHI M.R. & MINELLI G. (Eds.) (1998) - Results of the CROP03 deep seismic reflection profile. Mem. Soc. Geol. It., **52**, 657 pp.
- SAGE L., MOSCONI A., MORETTI I., RIVA E. & ROURE F. (1991) - Cross sections balancing in the Central Apennines; an application of LOCACE. Am. Ass. of Petrol. Geol. Bull., **75**, 832-844.
- SCARSELLA F. (1951) - Un aggruppamento di pieghe dell'Appennino Umbro-Marchigiano. Boll. Serv. Geol. d'Italia, **73**, 309-320.
- SIBSON R. H. (1985) - A note on fault reactivation. Journ. of struct. Geol., **7**, 751-754.
- TAVARNELLI E. (1997) - Structural evolution of a foreland fold-and-thrust belt: the Umbria-Marche Apennines, Italy. Journ. Struct. Geol., **19**, 523-534.

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