Thin-skinned vs. thick-skinned tectonics in the Matese Massif, Central–Southern Apennines (Italy)

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Abstract

Combined structural and geophysical investigations were carried out in the Matese Massif at the boundary between the Central and the Southern Apennines. The aim of this research was to define the structural geometry and the kinematics of Neogene deformation in order to validate the applicability of either thin-skinned or thick-skinned compressive styles in the Apennines of Italy.

On the basis of two surface N–S cross-sections, integrated with recently acquired magnetotelluric data, the Matese structure appears as a single thrust sheet limited at the bottom by a low-angle thrust fault with sense-of-displacement towards the North. The structure was later deformed by footwall thrusts carrying Molise–Sannio Pelagic Basin Units and Apulian Carbonate Platform Units.

The structure of the Matese Massif is composed mainly of Mesozoic carbonates of inner platform to by-pass and slope facies, separated within the thrust sheet by high-angle faults with low reverse horizontal displacement. These faults acted as normal faults in the Mesozoic and Cenozoic and controlled the carbonate facies distribution. During Neogene compression, these structures were tilted and then truncated by the basal short-cut thrust fault that cut from pre-Triassic units to Jurassic dolostone towards the foreland.

Finally, Quaternary extensional tectonics dissected the whole structure with fault-related displacement values of up to 1000 m. This resulted in the present-day structural setting of the Matese Massif as a horst bounded to the SW and NE by fault-controlled basins, filled with continental deposits.

This revised structural scenario is discussed within the framework of the structural style of external zones of the Apennines.

Keywords: Fold-and-thrust belt; Thin-skinned tectonics; Thick-skinned tectonics; Reactivation; Apennines; Matese; Italy

1. Introduction

The Apennine orogenic belt (Fig. 1) comprises Mesozoic and Cenozoic sediments that were deposit-

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1988; Mostardini and Merlini, 1986; Ghisetti et al., 1993; Cavinato et al., 1994).

In the Central and Southern Apennines, this model has led many authors to calculate large amounts of orogenic shortening (Calamita et al., 1994; Patacca et al., 1990; Cavinato et al., 1994; Finetti et al., 1996; Prosser and Schiattarella, 1998; Billi et al., 2001).

The timing of orogenic migration from the hinterland to the foreland has been defined by dating thrust-top and foredeep basins development through high-resolution stratigraphy (Patacca et al., 1990, 1992a; Cipollari and Cosentino, 1995). These data, coupled to thin-skinned model assumptions, support anomalously high shortening rates (tens of millimetres per year) if compared to the average shortening rates inferred from other fold-and-thrust belts (millimetres per year; Tozer et al., 2002).

However, recently acquired geophysical data support involvement of the magnetic basement in the Neogene deformation, even in the external portions of the Apennines. This is clearly shown along the crustal profile CROP 03 across the Northern Apennines (Barchi et al., 1998). Additionally, according to a recent interpretation (Chiappini and Speranza, 2002) of the new aeromagnetic map of Italy (Chiappini et al., 2000), basement involvement appears to be a widespread and distinctive feature throughout the front of the chain.

Furthermore, there have been plenty of recent contributions supporting a thick-skinned interpretation of the Apennine thrust belt. These are based on field data and commercial seismic lines, and explain the present-day structural setting of several sectors of the Apennines as a result of local contractional reactivation of extensional structures that pre-date formation of the thrust belt. This is testified by syn-tectonic facies changes in the Mesozoic and Cenozoic stratigraphy (Renz, 1951;
Fig. 2. Simplified geological map of the Central Apennines (after Accordi et al., 1988, redrawn and modified); refer to Fig. 1 for location. Most of this portion of the chain is formed by the stacking of the Apenninic carbonate Platform; the Apulia carbonate Platform outcrops in the Maiella Mountain, in the surrounding structures, and in the Gargano Promontory.
Giannini, 1960; Bernoulli, 1967; Colacicchi et al., 1970; Centamore et al., 1971; Decandia, 1982; Montanari et al., 1988; Winter and Tapponier, 1991) due to normal faulting as a result of the evolution of either the passive margin or the peripheral bulge (Adamoli et al., 1997; Coward et al., 1999; Tavarnelli et al., 1999; Mazzoli et al., 2000; Scisciani et al., 2000a,b, 2001).

This signature is widely recorded in the Northern Apennines (Umbria–Marche–Romagna pelagic domain and its transitional facies), where the role of reactivation processes is prominent in determining the thrust evolution and the present-day fault pattern (Cello and Coppola, 1989; Barchi and Brozzetti, 1994; Alberti, 2000). Pre-existing normal faults have not only affected the localization of thrust

Fig. 3. Satellite image of the Matese area. Main facies boundaries: continuous bold lines. Main Neogene compressive elements, locally reactivated by Quaternary extensional tectonics: dashed fine lines.
Fig. 4. Simplified structural map of the Matese Massif and surrounding areas.
ramps, the amount of local shortening, and the development of short-cut thrusts, but have also resulted in severe tilting and moderate rotations about vertical axes (Barchi et al., 1989; Adamoli, 1992; Tavarnelli, 1996; Alberti et al., 1996; Adamoli et al., 1997; Coward et al., 1999; Tavarnelli et al., 1999; Mazzoli et al., 2000, 2001a; Scisciani et al., 2000a, 2001).

Studies focusing both on local (Scisciani et al., 2000b) and regional scale structures (Corrado et al., 1998a; Scisciani et al., 2001, Tozer et al., 2002) also investigated the effect of pre-thrusting structures in the Central Apennines carbonate platform domains and at their boundaries with the surrounding pelagic basins.

Finally, in the Southern Apennines and Sicily, contractional reactivation mechanisms, as well as basement involvement in thrusting, are more scattered but still documented (Renda et al., 1999; Menardi Noguera and Rea, 2000; Mazzoli et al., 2000, 2001b).

In this framework, the structure of the Matese Massif, located at the boundary between Central and Southern Apennines (Fig. 2), represents a key area in which to test thin- vs. thick-skinned geometric models for three main reasons.

First, the massif (Figs. 3 and 4) shows a rather intricate Meso-Cenozoic paleogeography; a transition from Mesozoic thicker carbonate platform deposits to thinner Meso-Cenozoic slope deposits can be observed from south to north.

Secondly, the pre-orogenic facies boundaries strike almost parallel to the main Neogene compressional and transpressional features that overprinted them.

Finally, the Pleistocene geometry of the structure (i.e. at the end of compression), as derived from restored sections, is characterized by an anomalously high culmination in the southern sector of the Matese Massif. Its occurrence can be explained in two ways: either the relief was inherited, or it was caused by severe shortening and tectonic thickening of deeper thrust sheets in thin-skinned fashion.

In this paper, we address these two hypotheses by presenting two N–S geological sections through the Matese Massif. They are based on newly acquired field data and meso-structural analysis integrated with pre-existing (gravimetric anomalies and hydrocarbon wells) and new (magnetotelluric) subsurface data acquired for oil exploration. The sections have been restored to Lower Pleistocene times to remove the effects of Quaternary extensional tectonics. This allows the compression-related structural geometry and the timing of deformation to be defined. Finally, we discuss different hypotheses for the deep structure and the main deformation mechanism operating in the Matese area since the Messinian, and suggest their implications for oil exploration and for shortening amounts and rates.

2. Geological setting

The Apennine fold-and-thrust belt of peninsular Italy (Fig. 1) forms part of the Africa-verging mountain system in the Alpine–Mediterranean area. This area evolved within the framework of convergent motion between the African and European plates since the Late Cretaceous (Dewey et al., 1989). Roughly north–south convergence between Africa and Eurasia was dominant up to Oligocene time. During the Neogene, nearly east-directed thrusting toward the Apulian (or Adriatic) continental margin dominated and was accompanied at the hinterland by the opening of the Tyrrhenian Sea (Malinverno and Ryan, 1986; Royden et al., 1987; Mazzoli and Helman, 1994; Carmignani et al., 2001 and references therein). The Central Apennines (Fig. 2) developed in a transition area between the northern and southern arcs that make up the whole Apennine fold-and-thrust belt. They comprise sediments mainly derived from the Mesozoic deposits of the southern passive-margin of the Tethys Ocean. Therefore, the geological evolution of the region containing the Matese Massif (Figs. 3 and 4) can be traced back to the Mesozoic (Di Bucci et al., 1999).

Different paleogeographic reconstructions are available for this part of the Apennines (among others: D’Argenio et al., 1973; Mostardini and Merlini, 1986; Sgrosso, 1988; Pescatore, 1988; Cello et al., 1989; Marsella et al., 1992; Patacca et al., 1992a,b; Corrado et al., 1998a; Pescatore et al., 1999). A critical review of these models can be found in the work of Di Bucci et al. (1999), whose final reconstruction has been
adopted in this work. This reconstruction of the Mesozoic paleogeography for the passive margin stage shows two main carbonate platforms (the Apenninic and Apulia Platforms) separated by a pelagic basin (the Molise–Sannio Basin). Between the Late Tortonian and Late Pliocene p.p., these palaeodomains were progressively involved in the NE-verging orogenic system. Extensional faulting (due to flexure of the margin), development of a complex foredeep, and finally thrusting affected this segment of the pre-existing passive margin. The resulting tectonic stack forms the bulk of the present-day Central–Southern Apennines orogenic wedge. In general, sediments of the Apenninic carbonate Platform make up the Matese Massif, whereas related slope sediments and pelagic deposits outcrop in the northern Matese Massif, Montagnola di Frosolone, Sannio and Alto Molise; siliciclastic foredeep deposits primarily outcrop in the topographic depression between the Montagnola di Frosolone and the Matese Massif.

Between Late Pliocene p.p. and Early Pleistocene, the same compressional tectonic regime gave rise to widespread WSW–ENE to W–E trending left-lateral and N–S trending right-lateral strike-slip faulting, which resulted in the dissection of the thrust structures. The hypothesis that some of these faults cut through the entire thrust stack cannot be ruled out (Corrado et al., 1997a). In this period, an incipient extension involved the SW side of the Matese, opening the lower Voltumno River valley (Brancaccio et al., 1997).

Post-Messinian and pre-Middle Pleistocene tectonic activity was also responsible for a 40° counterclockwise rotation about vertical axes of the Montagnola di Frosolone and the northern portion of the Matese (Iorio et al., 1996; Speranza et al., 1998).

Finally, in the study area, the tectonic regime changed drastically during the Middle Pleistocene and a NE–SW oriented extension became dominant (Patacca et al., 1992a; Corrado et al., 1997b; Ferranti, 1997). Not only did this extension cause the formation of a system of NW–SE striking normal faults, but it also resulted in partial reactivation of the existing strike-slip faults with either an opposite sense of slip or a dip-slip component (Corrado et al., 1997b, 2000). As a result, the Matese Massif appears as a carbonate horst bounded by extensional intramontane continental basins (Di Bucci et al., 1999).

Furthermore, in situ stress data for the region (Montone et al., 1999) show a present-day stress pattern that is consistent with these observations, i.e. the same tectonic regime has acted since the Middle Pleistocene.

### 3. Field data

#### 3.1. General overview

The Matese Massif (highest peak: Mt. Miletto, 2050 m) is a roughly east–west oriented mountain ridge (Figs. 3 and 4). It is characterized by extensive outcrops of Apenninic Platform carbonate rocks and related transitional facies to the Molise–Sannio pelagic Basin to the north and east. The central and western parts of the structure were mapped in detail (1:25,000) and two roughly N–S oriented geological sections were drawn (Fig. 5). The massif can be subdivided into three sectors (southern, central, and northern) for both palaeoenvironmental and tectonic reasons (Figs. 3 and 4).

#### 3.2. Southern sector

Outcropping facies are predominantly of carbonate shelf, ranging from Upper Triassic dolostones to Upper Cretaceous limestones (Figs 5 and 6a–d). They are overlain by Middle Miocene ramp carbonates of the Cusano Formation, followed by Upper Miocene hemipelagic marls (Longano Formation) and siliciclastic foredeep deposits.

The Triassic dolostones, known as Fontegreca Formation, are extensively exposed between Raviscanina and Valle Agricola, along transect A–A’ (Fig. 5). Jurassic and Cretaceous facies are dominant between Mt. Capello and Letino (transect A–A’), and along transect B–B’ (Fig. 5). The bedding dips ca. 30° to the north along transect A–A’, while it forms an E–W trending open anticline along transect B–B’.

In this sector, brittle deformation is predominantly extensional; morphological features like triangular facets and alluvial fans provide evidence for its recent activity. NW–SE trending normal faults in the Raviscanina area and E–W trending faults in the Piedimonte Matese and San Gregorio...
Fig. 5. Cross-sections through the Matese Massif. Traces are drawn in Figs. 3 and 4. Southern, central, and northern sectors are described in the text. Mesoscopic structural data are plotted on lower hemisphere, equal-area projection (continuous lines and dots: faults and related poles. Dashed lines and triangles: bedding and related poles).
Fig. 6. Stratigraphic setting of the Matese Massif. Stratigraphic sections are representative of the southern, central, and northern sectors described in the text. Thickness of lithologies marked with the asterisk are derived from subsurface data.
Fig. 7. Geological map of the Gallo–Letino area and related mesostructural data (on lower hemisphere, equal-area projection; faults: continuous lines). A–A’ refers to part of the cross-section A–A’ in Fig. 5.
Fig. 8. Panoramic view of the northern edge of the Matese Lake. Note how extensional faults downthrow to the south of the block that contains the lake.
Matese areas downthrow their hanging-wall blocks to the southwest and to the south, respectively. These faults define the boundary of the Matese Massif with the Volturno River valley (Fig. 4).

The northern boundary of this sector is marked by an E–W trending major morphological lineament running across the central part of Matese. In the Letino area, (Fig. 7) the western tip of this lineament is marked by NE–SW trending high-angle left-lateral transpressive faults (plot “a” in Fig. 7). Moving eastwards, similar kinematics is observed along south-dipping ENE–WSW oriented high-angle faults. These mesoscopic structures can be interpreted as synthetic Riedel planes connected to a major E–W trending left-lateral fault (plot “c” in Fig. 7) that separates Letino’s Jurassic carbonates ridge to the south from the siliciclastic deposits of the depression of Gallo to the north.

The transpressional features are dissected by younger WNW–ESE oriented, SSW-dipping normal faults clearly visible along the northern slope of the valley (plot “b” in Fig. 7).

Farther east, the lineament deflects to a WNW–ESE strike and enters the valley containing the Matese Lake. In this area, it consists mainly of WNW–ESE striking south-dipping normal faults that repeatedly truncate the Lower/Upper Cretaceous boundary. Suspended valleys, triangular facets, and footwall-sourced alluvial fans suggest that recent extensional tectonics shaped the valley (Fig. 8). However, scattered pre-existing elements showing transpressional kinematics are still preserved west of the lake.

A distinctive tectono-stratigraphic feature of this sector is observed in the Valle Agricola and San Gregorio Matese areas. At the highest peaks south of Valle Agricola (Mt. San Silvestro, 1083 m a.s.l.), mainly pelitic-arenaceous, rarely turbiditic deposits of probable Upper Miocene age containing Miocene carbonate olistoliths lie unconformably on...

Fig. 10. Panoramic view of the eastern edge of Gallo depression (Monticello hill). Note the stratigraphic unconformity between Triassic dolostones (Fontegreca Formation) at the bottom and Upper Cretaceous–Paleocene limestones (Monte Calvello Formation) at the top.

Fig. 9. Geological map of the San Gregorio area and related mesostructural data (on lower hemisphere, equal-area projection; faults: continuous lines). Note the angular unconformity between the carbonate substratum and the Miocene siliciclastics, and the Quaternary extensional faults that downthrow the structure to the south. These faults are generally characterized by high dip angles and dip-slip kinematic indicators shown on plots a–d. B–B’ refers to part of the cross-section B–B’ in Fig. 5.
Triassic dolostones. The stratigraphic contact is marked by a hardground. A carbonate poligenic continental conglomerate that makes up the highest peaks lies unconformably on top of the siliciclastic sequence.

The situation is to some extent repeated farther east in the San Gregorio Matese area (Fig. 9). Here, mostly pelitic, siliciclastic deposits, containing Miocene carbonate olistoliths and breccias, lie unconformably both on Cretaceous (south of San Gregorio Matese) and on Miocene carbonates (north of San Gregorio Matese). They are found at three different elevations, bounded by E–W oriented south-dipping normal faults. Again, on top of the carbonate/siliciclastics contact, well cemented and bedded continental conglomerates are found.

![Fig. 11. Simplified geological map of Matese anticline area and related mesostructural data (on lower hemisphere, equal-area projection; faults: continuous lines; poles to bedding: triangles; hinges: slashed dots). A–A’ refers to part of the cross-section A–A’ in Fig. 5.](image-url)
Fig. 12. Simplified logs of wells drilled in the surroundings of the Matese Massif. Location in Fig. 15.
3.3. Central sector

Outcropping facies are predominantly of carbonate shelf and by-pass margin, ranging from Upper Triassic dolostones to Upper Cretaceous limestones (Figs. 5 and 6e–f). The distinctive stratigraphic feature of this sector is represented by the Upper Cretaceous/Paleocene transgressive cycle that covers progressively younger units from west to east (Ietto, 1963, 1969). In detail, in the area of Capriati a Volturno and Fontegreca, as well as in the depression of Gallo, bio-sparitic carbonates deposited in slope environment (Monte Calvello Formation) rest directly on top of Upper Triassic dolostones. Near Gallo, this contact is marked by a slight angular unconformity (Fig. 10). Farther east, north of the highest peak Mt. Miletto, the Monte Calvello Formation lies in paraconformity on Lower Cretaceous inner shelf carbonates.

The Mesozoic–Paleocene sequences are generally overlain by the Middle Miocene ramp carbonates of the Cusano Formation lying paraconformably on top of the Monte Calvello Formation. They consist of Bryozoa- and Lithotamnium-rich carbonate ramp grainstones. As the depositional marine environment became deeper during Middle to Upper Miocene, Orbulina-rich marls and shales were deposited and finally evolved to flysch sedimentation (Fig. 6e). This evolution is quite clearly exposed in Gallo area (Fig. 7).

Moving to the north, Eocene to Oligocene calcarenites of the Monaci Formation containing Nummulitidae and Alveolinidae, and Lepidocyclinae-bearing shales of the Macchiagodena Formation, are rarely comprised between Mesozoic–Paleocene and Miocene sequences. They are exposed in the Mt. Celara area.

In this sector, brittle deformation is predominantly extensional. It is clearly exposed along transect B–B’ (Fig. 5). In fact, between the Matese Lake and the San Massimo valley, the massif shows a horst structure limited by E–W and NW–SE oriented normal faults; the structure corresponds to the highest peaks Mt. Miletto and La Gallinola. The northernmost fault, a NW–SE striking, NE-dipping normal feature, results in the boundary of the Matese carbonates with the San Massimo valley, where siliciclastic sediments border the massif to the north.

The boundaries with the adjacent sectors are marked instead by transpressional elements to the south and compressive faults to the north.

In the depression of Gallo (850 m a.s.l.), the transpressional left-lateral fault that marks the southern boundary is associated with tight folds with E–W to NW–SE trending axes developed at its footwall in hemipelagic marls and siliciclastics. The northern boundary is marked by a fault-propagation anticline well exposed along transect A–A’ (Fig. 5) with an east–west trending axis (the Matese anticline; De Corso et al., 1998). The fold becomes more and more open and dies out both to the west and to the east. The related fault develops for about 4 km in the central part of the structure and shows a maximum reverse separation of less than 100 m (De Corso et al., 1998). It is marked by low-angle, south-dipping fault planes with reverse dip-slip kinematics that indicate the top-to-the-north displacement of the structure (plot “a” in Fig. 11).

3.4. Northern sector

In the northern sector, the sedimentary deposits are deeper marine and show transitional facies to the Molise–Sannio pelagic sequence. It is characterized by the extensive outcrop of the Monte Calvello, Monaci, and Macchiagodena Formations and by the lens-shaped transgressive Middle Miocene grainstones that are time-equivalent to the Cusano Formation. All these formations thicken gradually to the north toward the Frosolone area,
testifying the progressive deepening of the Meso-Cenozoic sedimentary basin. The succession evolves into siliciclastic sedimentation through *Orbulina*-rich marls (Longano Formation), which outcrops extensively north of the Matese anticline. The buried portion of the slope-to-basin succession has been penetrated by the Frosolone 2 well (Fig. 12). It ranges from Upper Jurassic/Lower Cretaceous calcareous conglomerates, dolostones, and cherty shales of the Indiprete Formation to Upper Cretaceous micritic limestones with chert and fragments of rudists of the Monte Coppe and Coste Chiavarine Formations (Scrocca and Tozzi, 1999).

In this sector, brittle deformation is predominantly extensional, with NW–SE oriented high-angle normal faults downthrowing the Matese Massif carbonates to the NE beneath the Boiano basin.

Furthermore, between Longano and Castelpizzuto (Fig. 4), Upper Cretaceous to Miocene slope facies carbonates outcrop in small structural highs bounded by N–S trending faults, which mainly dip to the east. They first acted as right lateral faults and since the Middle Pleistocene have been probably reactivated as transtensive left-lateral faults (Corrado et al., 1997b).

Finally, the boundary with the central sector is marked by the Matese anticline (Fig. 11). Its footwall is deformed in an E–W trending, major recumbent syncline associated with mesoscopic chevron folds (plot “b” in Fig. 11).

4. Restoration of extensional tectonics

Although the Matese Massif experienced important thrusting during the building of the Apennine chain, little evidence of compression characterizes this structure and the brittle deformation is predominantly extensional.

In fact, it is a horst bounded by major NW–SE striking high-angle planar normal faults that downthrow the carbonates to the SW for at least 1000 m and to the NE for a few hundred metres. The heart of the massif is also severely affected by analogous fault systems; these are characterized by lower vertical displacements (mainly from tens to hundred of metres). In some cases, pre-existing N–S and E–W striking strike-slip faults have been reactivated as transtensional faults presumably by the onset of NE–SW oriented extension that has acted in the area since Middle Pleistocene (Corrado et al., 1997b).

In order to understand the geometry of the pre-extensional setting, we restored the two sections of Fig. 5 by removing the effects of the recent extensional deformation occurred on planar non-rotational faults. The planar geometry of the faults that affect the southern portions of the two sections represents one of the distinctive features of extension in the Matese Massif. This is evident not only from geometric surface data, but also from seismological information about the faults that border the Matese Massif to the NE and that ruled the development of the Boiano basin (Cucci et al., 1996; Corrado et al., 2000). Furthermore, the non-rotational kinematics, even though not a widespread feature at the regional scale and in the Apennines, seems to be the best approximation we can propose for the faults along the two transects. As a matter of fact, in the southern portions of the sections the average dip of the bedding (approx. 30–35°), associated to faults dipping from 60° to 70°, is not consistent with rotational planar faulting as described by Wernicke and Burchfiel (1982). In fact, had we assumed a tilting, rotating the fault-bounded blocks back during restoration would have caused the normal faults to reverse their dips. Moreover, the total amount of the inferred net extension is very low: 3.1 over 22.2 km (+14%) for the section A–A′, 1.6 over 18.8 km (+9%) for the section B–B′ (see Figs. 13...
and 14). These values, associated with the faults’ average dip and the total displacement along the array of faults in the southern sector, are consistent with the non-rotational normal fault model discussed by Wernicke and Burchfiel (1982).

Unfortunately in the study area, as in many cases in the Apennines, the best tool to test rotational vs. non-rotational kinematics, i.e. the stratal architecture of syn-tectonic deposits within fault-bounded depressions, cannot be applied due to the lack of these deposits. Therefore, rotational models like the domino-like faulting cannot be definitely ruled out. However, applying this model to fault blocks of about 1 km and with a dip of 60° (modeling the normal faults of Figs. 13 and 14), rotations near to 30° are necessary to reduce to zero a mean displacement of 0.5 km (trigonometric computations can be easily developed, based on formulas after Mandl, 2000). In this way, extensional faults would have developed with dips near to 90°, in contrast with the Anderson model.

Based on these considerations, a non-rotational model is proposed in this paper for the restoration of the Quaternary extensional faults that dissect the compressional structures.

Both restored sections show a prominent structural culmination in their southernmost portions, where the bedding dips to the north, with steeper angles (40° average) in the western section (section A–A’) than in section B–B’. This culmination needs a suitable structural explanation in the subsurface setting of the area.

5. Subsurface data

5.1. New magnetotelluric data

The Edison Gas Company recently performed a new magnetotelluric survey in order to collect subsurface data in this area. Twenty-three magnetotelluric soundings were carried out on the Matese Massif, obtaining quite good quality results (see Fig. 15 for location). The stations were laid out along two dip lines oriented approximately N–S and along a NW–SE strike line. The distance between the stations was nominally 2 km. Two isolated soundings were also made at the locations of the Campobasso 1 and Morcone 1 wells.

Afterwards, 2D inversion processing was carried out along the two N–S transects (1–1’ and 2–2’ in Figs. 15 and 16) that roughly correspond to the two surface sections presented above (Fig. 5). The transects show comparable patterns of anomalies arranged in three principal layers, characterized by different values of apparent resistivity. From the surface below, they are arranged as follows (Fig. 16):

- an upper high-resistivity layer showing its maximum thickness where both transects reach the highest topographic elevations (Mt. Celara for the western section and Mt. Miletto for the eastern section);
- an intermediate low-resistivity (high conductivity) layer that thins out at the southern edge of both processed profiles; it is noteworthy that the lack of data at the edges of the acquired MT grid could give a low statistic control of the modelling;
- a lower high resistivity-layer.

The processing performed on all the recorded soundings provides a high degree of reliability for the upper layer and the underlain conductive unit. The thickness of the conductor and the transition to the lowermost resistive unit is less reliable due to the impact of noise recorded at lower frequencies.

5.2. Magnetotelluric interpretation on the base of pre-existing subsurface data

No seismic data have yet been acquired on the Matese Massif for oil exploration. Thus, a reliable interpretation of the magnetotelluric data can only be drawn on the basis of subsurface data acquired in more external areas (deep wells and seismic lines) and Bouguer gravity anomaly map of the massif and its surroundings (Mostardini and Merlini, 1986) (Figs. 12, 15, 16, and 17).

A correlation between the magnetotelluric pattern and the geological units is straightforward only for the upper resistive layer that corresponds to carbonates of the Matese thrust sheet (Apenninic Platform domain). At depth, this thrust sheet is testified, for example, by the Campobasso 1 well (Fig. 12) in which a thick Mesozoic carbonate sequence was encountered. It evolves to slope deposits in Cretaceous–Eocene and is overlain by Miocene ramp carbonates and Upper
Miocene siliciclastics. This sequence strictly correlates with the typical outcropping sequence in the northeastern Matese Massif.

The lower resistive layer could correspond to the buried Apulia Platform carbonates, as suggested by the reconstruction of the regional setting beneath the external areas of Central and Southern Apennines (Mostardini and Merlini, 1986; Cello et al., 1989; Roure et al., 1991; Mazzoli et al., 2000, 2001b). The buried Apulia Platform’s structural setting has been widely investigated in the last decade since it shows a high potential as a hydrocarbon reservoir (Casero et al., 1991). It is made up of Mesozoic and Tertiary carbonates up to 6–7 km thick, stratigraphically overlain by marine siliciclastics of Messinian–Pliocene age.

The nearest wells to the study area that reached the top of the buried Apulia Platform are the San Biase 1...
and Castelmauro 2 wells (Fig. 12); they penetrated the Apulia carbonates at a mean depth of about 3400 m, comparable with the depth of the top of the lower resistive layer.

More speculative is the geologic significance of the intermediate conductive layer. The low values of apparent resistivity could suggest a clay-rich composition. In addition, correlation with the subsurface position of the Matese thrust sheet, which is known to the north and to the east of the study area (Scrocca and Tozzi, 1999 and Fig. 17; Corrado et al., 1998b; Mazzoli et al., 2000), suggests that at least the northernmost portion of the conductive layer in the sections of Fig. 16 could belong to the pelagic basin clastic successions of the Molise–Sannio domain. This is confirmed, for example, by the sequence
drilled at the bottom of the Frosolone 2 and Campobasso 1 wells, and by the geologic interpretation of a seismic line acquired to the east of the Matese Massif (Fig. 17). Therefore, these pelagic sequences could represent the intermediate structural unit between the internal Apenninic and the external Apulia Platform, as imaged in the northern portions of the magnetotelluric transects. In fact, moving toward the foreland, the wells external to the Matese thrust sheet show that the Molise–Sannio sequences are thrust over the Apulia Platform (e.g., San Biase 1 and Castelmauro 2 wells in Fig. 12).

On the other hand, south of Letino and Matese Lake latitudes, subsurface data are different: the low-resistivity layer becomes shallower and also thins out to the south along both transects, and positive Bouguer anomalies reach the highest values (>12 mgal). Therefore, as opposed to the northern parts, data derived from the external areas do not provide a solid constraint to interpret the southern portions of the transects.

6. Discussion

Along the western transect through the Matese Massif, the main Meso-Cenozoic facies boundaries (carbonate platform/by-pass margin to the south, by-pass margin/slope to the north) roughly correspond to the main compressive and transpressive faults (Fig. 5). These are characterized by low horizontal displacement (from a few tens of metres to zero). This evidence suggests that pre-thrusting local facies distribution was only slightly affected by Neogene deformation. We interpret these abrupt facies changes to be the result of normal faulting that was active during the evolution of the passive margin. According to traditional models of platform margin geometry (Winterer and Bosellini, 1981), this is most likely for the boundary between the carbonate platform (south of Letino village) and the by-pass margin facies (north of Letino). In this hypothesis, the carbonate platform facies corresponds to a structural paleo-high with respect to the rest of the section (Fig. 18).

Furthermore, Miocene siliciclastic deposits in the southern area around Valle Agricola and San Gregorio Matese generally show proximal facies. They are transgressive onto a pre-deformed carbonate substratum that is deeply eroded and becomes progressively younger from west (Triassic) to east (Cretaceous–Miocene). This evidence testifies a severe erosional event predating their deposition.

Two hypotheses based on these data are possible:

- pre-thrusting basins developed on a pre-existing structural high in the early stages of Upper Miocene foredeep evolution;
piggy-back basins (sensu Ori and Friend, 1984) developed on the already formed thrust belt.

No detailed stratigraphic data are available for these deposits: they contain Middle Miocene carbonate olistoliths and are topped by Quaternary continental breccias. Unfortunately, these constraints are not sufficient to discriminate between the two hypotheses. Nevertheless, their occurrence on top of a pre-existing and deeply eroded Mesozoic structural highs seems to support the first hypothesis better. In fact, had the deposits been piggy-back basins, the rate of erosion between the foredeep stage and the piggy-back deposition would have been unrealistically fast (approx. more than 2 mm/year) when compared to an average uplift rate of about 1 mm/year for the Southern Apennines in Quaternary times (Di Leo et al., 2001).

Finally, the restoration of extensional faults highlights a strong pre-Quaternary structural culmination in the southern Matese Massif. This culmination has been explained considering both surface and subsurface geometries of the structural units involved in this segment of the chain. The magnetotelluric transects strengthen the assumption that the Matese thrust sheet, the carbonates of which correspond to the upper resistive layer of Fig. 16, is detached from its sub-stratum. This is supported by the fact that the lower resistive layer, probably corresponding to the Apulia carbonate unit, is continuous in the subsurface along the entire sections. Furthermore, in the southernmost portion of the two transects, the lower resistive layer (seemingly Apulia Platform unit) is uplifted. As a consequence, the above-mentioned culmination is at least partially due to the buried Apulia unit that deformed the overriding thrust sheet according to a piggy-back sequence of thrusting.

Nevertheless, especially along the western transect, this buried culmination is not sufficient to explain the structural relief of Figs. 13 and 14, and two hypotheses can be suggested (Fig. 19). In the first, the Matese thrust sheet is totally detached at the base of the carbonates in a typical thin-skinned style (Fig. 19a). In this case, thickening of the intermediate (clay-rich) structural unit as a result of localized shortening would have further contributed to the structural culmination. A similar hypothesis has been recently proposed for other external structures of the Apennines by Billi et al. (2001) and Patacca and Scandone (2001).

In the second hypothesis, we envisage the presence of a pre-carbonate basement of conspicuous thickness beneath the carbonates of the Matese thrust sheet (Fig. 19b) that could correlate to the culminated portion of the conductive layer of Fig. 16. Furthermore, it could be characterized by high gravity anomalies, as recognised for the pre-Triassic basement in the Northern Apennines along the CROP 03 transect (Barchi et al., 1998; Larocchi et al., 1998) and suggested for the Central–Southern Apennines by Rapolla (1986). This unit could have been preserved at the bottom of the Mesozoic–Cenozoic structural high, lying at the footwall of pre-existing normal faults (Fig. 19c.1), which were tilted at the beginning of compression (Fig. 19c.2) and then passively detached from their substrate by the low-angle Matese basal thrust (Fig. 19c.3).

The tilting of these faults (Fig. 19c.1 and c.2) requires a substantial amount of simple shear. In the study area, evidence for this is provided by the numerous and well-known detachment layers within the stratigraphic succession; details are described by Di Luzio et al. (1999). These field data allow the interpretation of simple shear as mainly accommodated by discrete slip on sub-horizontal detachments. In turn, a significant development of simple shear introduces distortion on the pin-lines of the cross-sections; this remains an open problem and results in a higher degree of approximation in the restoration of the two cross-sections proposed.

The first hypothesis (thin-skinned style) seems unreliable for this area because the low-resistivity layer of Fig. 16 thins out. This indicates that the localized shortening hypothesis is incorrect, since it would require thickening beneath the structural culmination and probably lower gravity anomalies (see Fig. 15). Therefore, we suggest that the second hypothesis is more likely to be correct, although direct exploration would be necessary to confirm it. Nevertheless, pieces of field evidence of normal faults developed during the passive margin and foredeep stages have been described in the paragraph about field data and discussed at the beginning of this paragraph. Evidence of local contractional reactivation of these pre-existing faults has been recognised.
in the field; some of them fulfil the criteria defined in the work of Holdsworth et al. (1997). These criteria can be summarised as follows:

- difference of thickness and facies of the Meso-Cenozoic sequences to the north and to the south of the reactivated faults;
- high values of cut-off angles along the reactivated portions of pre-existing faults;
- low net displacement due to compression when compared to high displacement on the basal low-angle thrust.

7. Conclusions

This study of the Matese area provides new data concerning the structural setting of both the massif and its subsurface. New data have been used to test different models of compressive tectonic styles for the evolution of the Apennines chain during Neogene.

The integration of new field and magnetotelluric data with published subsurface data indicates that the Matese Massif represents a whole thrust sheet limited at the base by a low-angle thrust fault. Within the massif, pre-thrusting features are preserved, with only mild reactivation coupled to local intense mesoscopic deformation.

As a consequence, in our final interpretation, local contractional reactivation of pre-existing passive margin faults replaces regional low-angle short-cut faults. Therefore, we agree that “the processes of collision orogenesis are not merely the scaled up versions of those which operate during inversion of sedimentary basins” (Butler, 1989) and that discriminating between the two requires careful analysis of both surface and subsurface data.

Fig. 19. Two alternative hypotheses of the deep structure of the Matese Massif: (a) thin-skinned style; (b) combined thin-skinned/thick-skinned style; (c) sequence of deformation for hypothesis “b”. See text for a discussion.
In summary, two different shortening processes have operated in the Matese area. This suggests that inversion and thin-skinned tectonics superimpose as a result of the complex interplay between the articulated pre-orogenic architecture of the passive margins (Williams et al., 1989) and the mechanisms of thrusting along low-angle thrust surfaces (Dahlstrom, 1969; Butler, 1982; Boyer and Elliot, 1982).

Therefore, the development of petroleum plays in the external portion of the Apennines must take into account the complex interaction between thin- and thick-skinned style recently discussed at a regional scale by Mazzoli et al. (2000) and Butler et al. (in press).

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