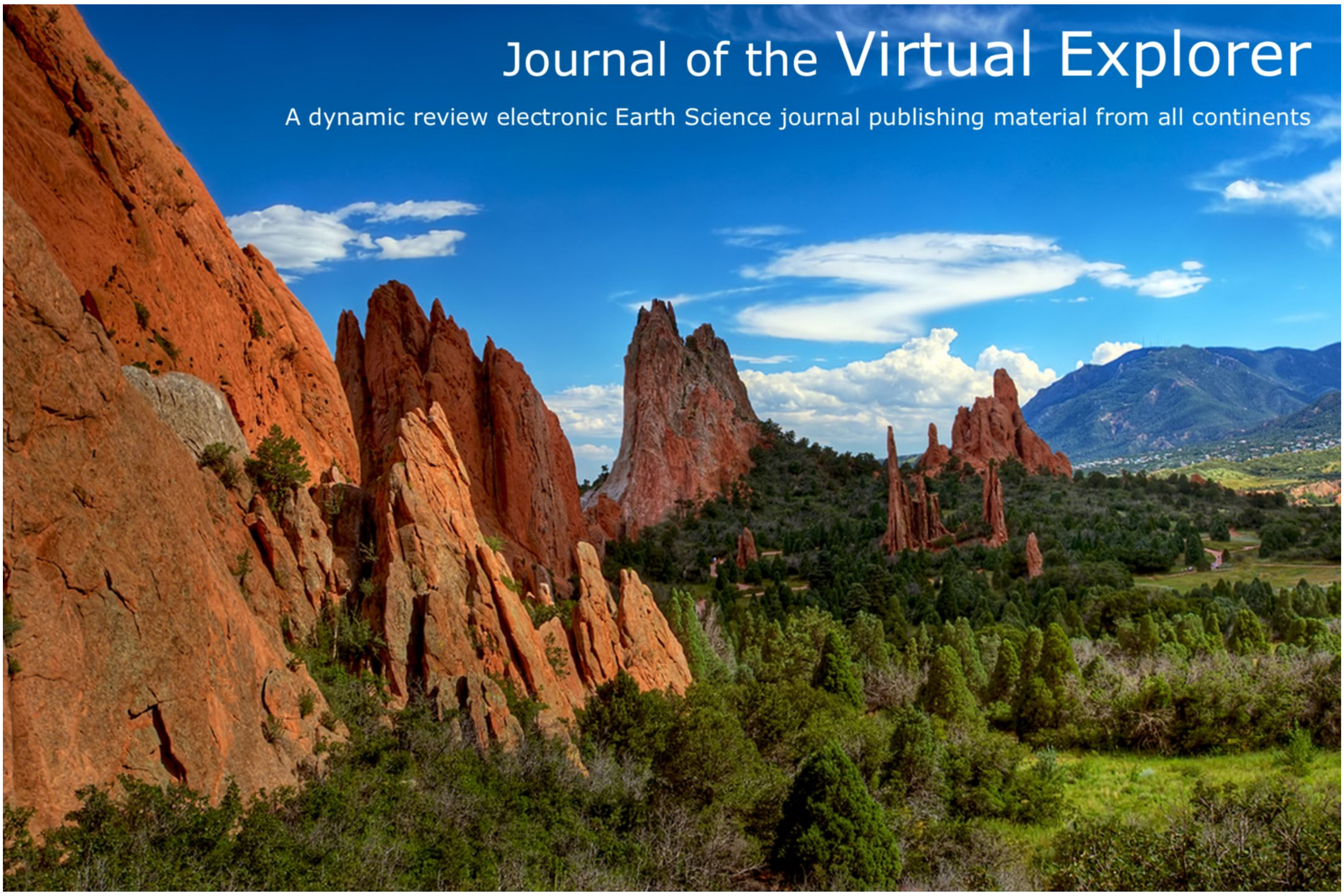

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Southern Apennines: structural setting and tectonic evolution

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Abstract: The Southern Apennines thrust belt, a roughly NW-SE oriented segment of the Apennines, is located in the hanging wall of a W-directed and E-retreating subduction of the Apulo-Adriatic lithosphere. The accretionary prism migrated from west to east since the Early Miocene being followed by coeval extensional tectonics which, progressively, cross-cut the thrust-sheets.

The development of the Southern Apennines accretionary prism occurred through the off-scraping and incorporation at the subduction zone of the Meso-Cenozoic passive margin sedimentary covers, which overlay the subducted Apulo-Adriatic crystalline basement, and the associated foredeep deposits.

Beneath the mountain chain the Apulian platform shallow water carbonates are deformed to shape a buried antiformal stack, whose structure at depth is poorly constrained by the available data. As a consequence, both thick- and thin-skinned models have been proposed. In these contrasting models significant differences regard: i) the shortening in the accretionary prism (particularly within the buried Apulian thrust units), and ii) the degree of involvement of the lower plate basement (i.e., the Apulian crystalline basement).

However, although it remains possible that the upper few kilometres of the Apulian basement could have been involved in thrusting, an integrated analysis of documented tectonic, geophysical and geochemical features shows that the thin-skinned model is generally more consistent with the available data.

In the preferred thin-skinned model, the total shortening of the allochthonous units (i.e., Apennine and Apulian Carbonate platforms and Lagonegro basin) is estimated to be greater than 280-300 km, while about 90 km of shortening can be attributed to the Apulian thrust units.

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Introduction

The southern segment of the Apennine orogen (Fig. 1) represents an ideal natural laboratory to study the complex interaction between tectonic and sedimentary processes responsible for the structural architecture of a thrust belt. Furthermore, the intense hydrocarbon exploration, carried out particularly during the 1980-2000 period, made available high quality subsurface dataset (seismic reflection and well data) whereas surface geology researches provided robust structural and stratigraphic constraints. Thus, the Southern Apennines thrust belt provides a challenging mixture of high quality data and poorly documented geological features that make fruitful the scientific debate about its geodynamic setting and tectonic evolution (e.g., Mostardini and Merlini, 1986; Casero *et al.*, 1988; Cello *et al.*, 1989; Patacca and Scandone, 1989; Roure *et al.*, 1991; Marsella *et al.*, 1995; Doglioni *et al.*, 1996; Lentini *et al.*, 1996; Monaco *et al.*, 1998; Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000; Patacca and Scandone, 2001; Lentini *et al.*, 2002; Carminati *et al.*, 2004; Catalano *et al.*, 2004; Butler *et al.*, 2004; Shiner *et al.*, 2004; Turrini and Rennison, 2004; Sciamanna *et al.*, 2004; Scrocca *et al.*, 2005, 2007; Mazzotti *et al.*, 2007; Patacca and Scandone, 2007a; Steckler *et al.*, 2008)

As an example, the deep tectonic setting, although partly illuminated by geophysical derived information such as, crustal refraction and reflection surveys, shear waves attenuation, seismic tomography (e.g., Scarascia *et al.*, 1994; Mele *et al.*, 1997; Improta *et al.*, 2000; De Gori *et al.*, 2001; Mazzotti *et al.*, 2007; Panza *et al.*, 2007; Steckler *et al.*, 2008 and references therein), is still a matter of scientific debate regarding mainly: i) the shortening in the accretionary prism particularly within the deepest thrust sheets in the Southern Apennines thrust belt (i.e. the Apulian carbonate platform units), and ii) the degree of involvement of the lower plate basement (i.e., the Apulian crystalline basement).

As a result, these uncertainties have produced significantly different interpretations of the Southern Apennines structure at depth deeper than 10 km, while the main tectonic features represented in published cross-sections at shallower levels are relatively similar. These different interpretations may be placed in the following two main groups (Fig. 2).

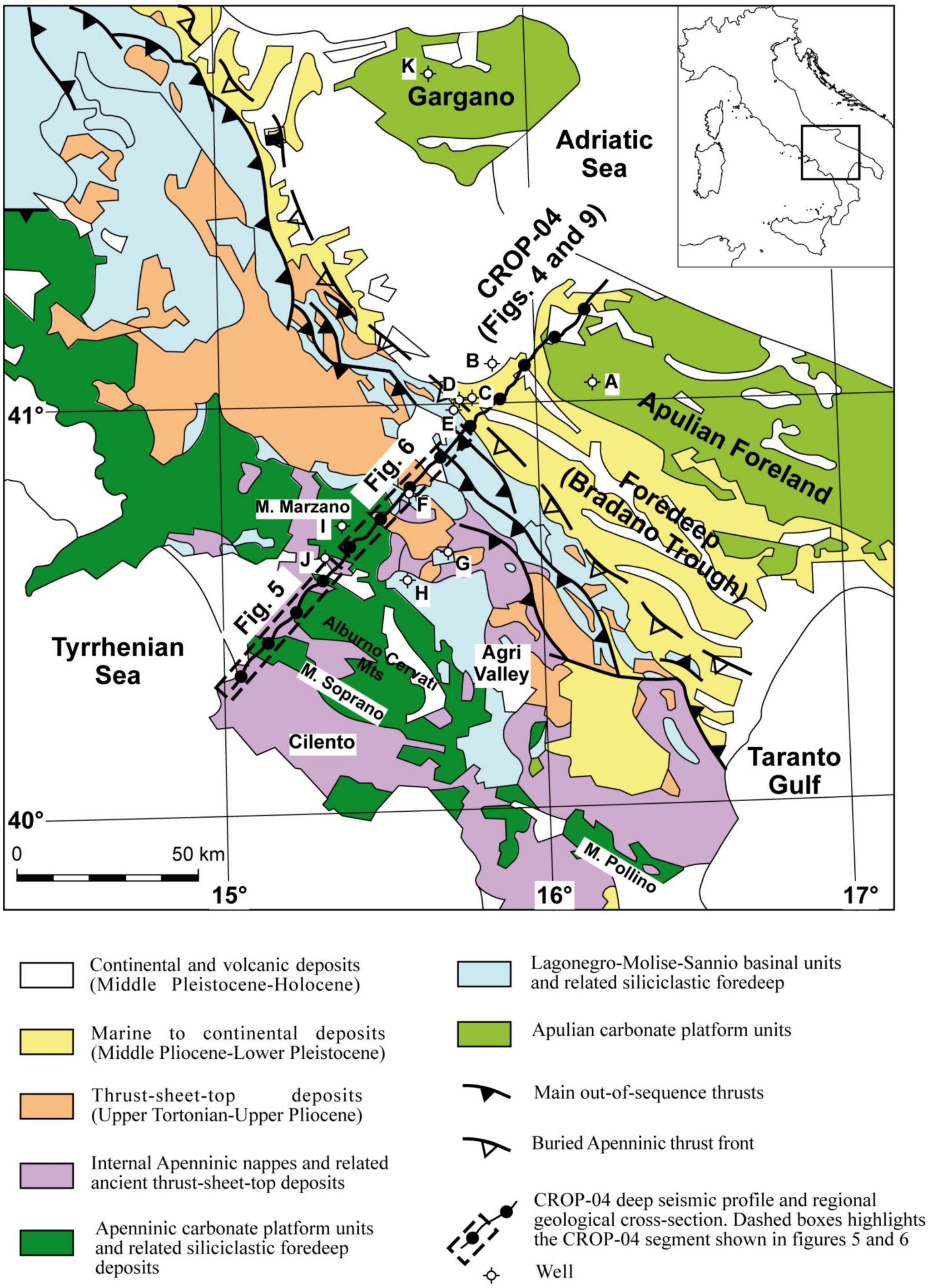
• In the first group (Fig. 2a), the possible existence of a basement wedge is suggested that corresponds to the classic backstop proposed for most of the Alpine and Cordillera types of orogen (e.g., Casero *et al.*, 1988; Roure *et al.*, 1991; Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000; Speranza and Chiappini, 2002; Sciamanna *et al.*, 2004). The shortening within the Apulian thrust units is small, in the order of 15-25 km (e.g., Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000).

• In the second group (Fig. 2b), the Southern Apennines thrust belt is considered to be mostly composed of sedimentary cover while the crystalline basement remains essentially undeformed. Two different geometries have been hypothesized for the Apulian crystalline basement. In a first hypothesis, the basement dips to the west under the thrust belt, with an almost constant attitude (Mostardini and Merlini, 1986; Marsella *et al.*, 1995; Mazzotti *et al.*, 2000; Patacca and Scandone 2007a). In a second hypothesis the basement top follows the flexural geometry of the subducting Apulian slab (Doglioni *et al.*, 1996; Scrocca *et al.*, 2005 and 2007). In the thin-skinned model, shortening within the Apulian thrust units are of at least 110-120 km (e.g., Mazzotti *et al.*, 2000).

An updated review of the structural architecture and tectonic evolution of the Southern Apennines has been carried out taking into consideration the stratigraphic and structural constraints provided by almost forty years of petroleum exploration.

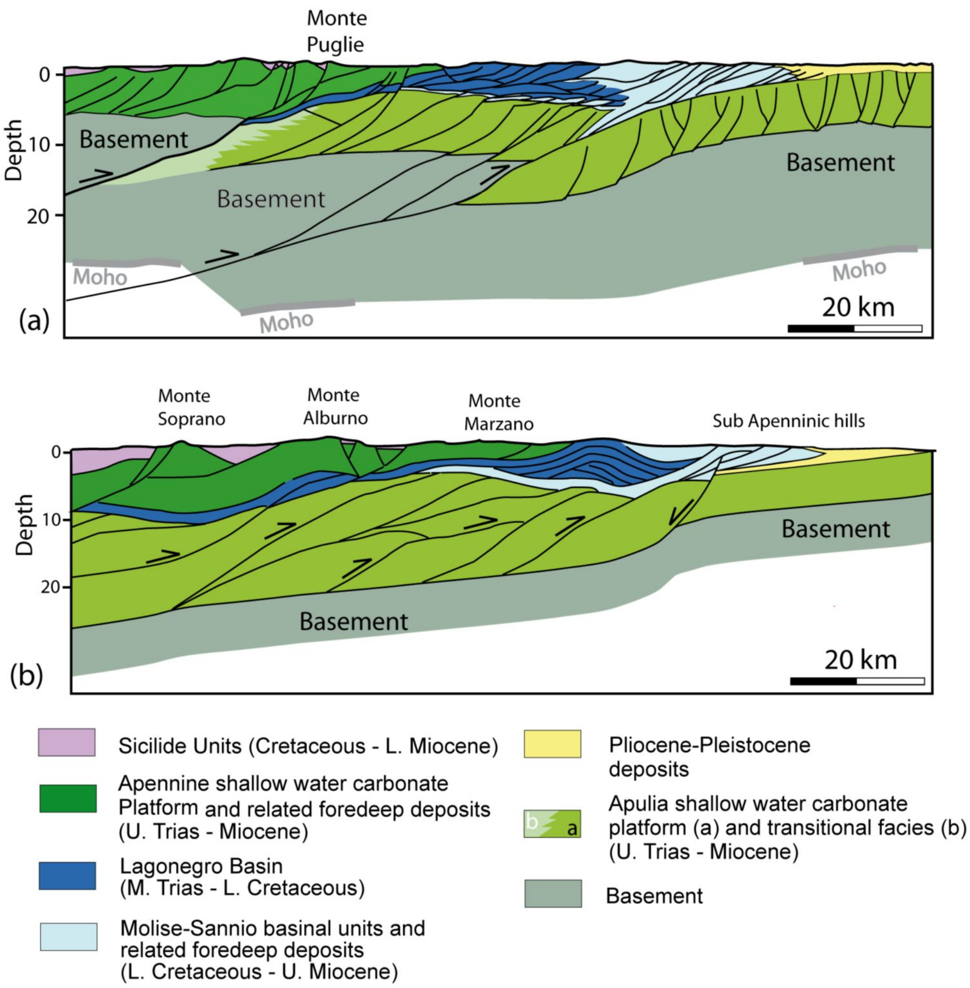
The main features of the southern segment of the Apennine orogen are described and discussed on the base of a regional geological cross-section drawn nearly parallel to the CROP-04 deep seismic reflection profile (Mazzotti *et al.*, 2000; Mazzotti *et al.*, 2007), which traverses the entire Southern Apennines from the Tyrrhenian to the Adriatic Sea.

Figure 1. Simplified geological map of the Southern Apennines



Simplified geological map of the Southern Apennines (modified after Patacca *et al.*, 1992 and Patacca and Scandone 2007). The location of the geological cross section and segments of the CROP-04 profile shown in this paper are highlighted. Letters identify relevant wells (A, Puglia 1; B, Gaudiano 1; C, Bellaveduta 1; D, Lavello 5; E, Lavello 1; F, S. Fele 1; G, M. Foi 1; H, Vallauria 1; I, S. Gregorio Magno 1; J, Contursi 1; K, Gargano 1).

Figure 2. Contrasting interpretation about the deep structural setting of the southern Apennines



Comparison between published thick- and thin-skinned interpretation of the deep structural setting of the Southern Apennines (modified after Scrocca *et al.*, 2005). a) Thick-skinned model with the crystalline basement largely involved by thrusting and small shortening in the Apulian carbonates (modified after Menardi Noguera and Rea, 2000). b) Thin-skinned model with rootless sedimentary nappes and large shortening in the buried Apulian thrust sheets (modified after Mazzotti *et al.*, 2000).

Geological framework

The Southern Apennines fold-and-thrust belt (Fig. 1) developed during Neogene and Quaternary times along an eastward-retreating west-directed subduction zone. Starting from Early Miocene the subduction retreat caused the progressive eastward migration of the foreland flexure, thrust fronts, and of the extensional backarc tectonics, which migrated from the Tyrrhenian Sea to on-land intra-mountainous basins (e.g., Malinverno and Ryan, 1986; Royden *et al.*, 1987; Patacca *et al.*, 1990; Doglioni, 1991; Doglioni *et al.*, 1999). The progressive propagation of the contractional deformation towards the foreland is clearly documented by the development and evolution of a series of eastward-younging foredeep basins and by the occurrence of several piggy-back basins that developed on top of the advancing allochthonous units (Patacca and Scandone, 1990, 2001). Starting from the middle Miocene, the tectonic accretion within the thrust belt has been contemporaneous with extensional tectonics along the Tyrrhenian margin which produced thinning of the internal sectors of the belt (Casero *et al.*, 1988; Patacca *et al.*, 1990; Cello and Mazzoli, 1999). During the Late Pleistocene, the subduction retreat appears to have slowed in response to the interference of the thick continental Apulian lithosphere with the front of accretionary prism (Doglioni *et al.*, 1994).

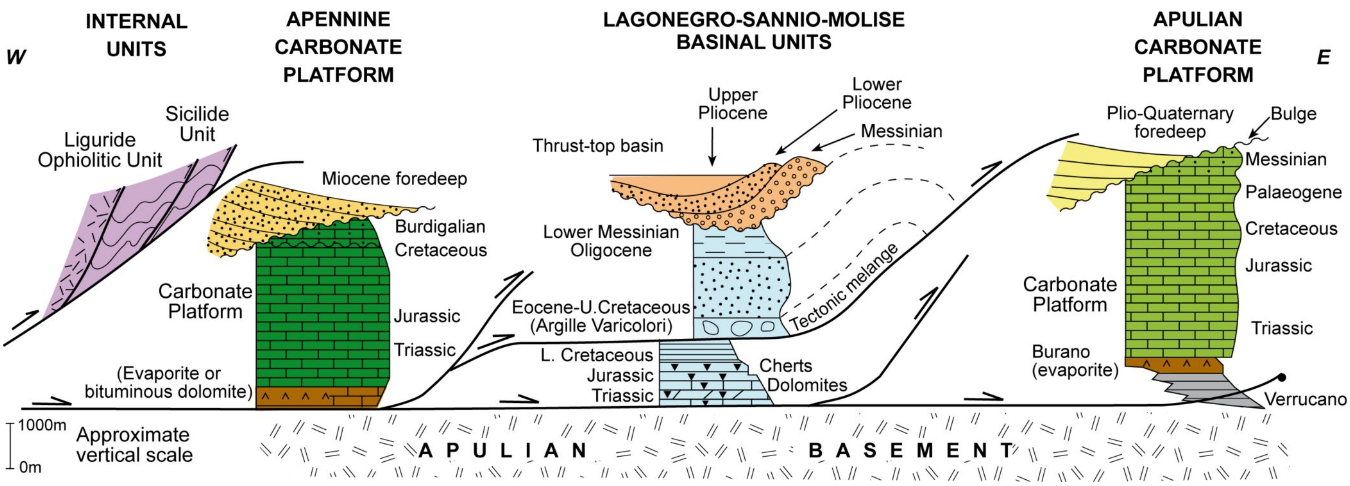
During the subduction hinge rollback, the Meso-Cenozoic passive margin sedimentary cover of the subducting Apulo-Adriatic plate was offscraped and piled up to form the Apennines accretionary prism.

Due to the very complex geological setting of the Southern Apennines several, often conflicting, paleogeographical models have been proposed for the passive margin of the Adriatic plate (D'Argenio *et al.*, 1975; Mostardini and Merlini, 1986; Casero *et al.*, 1988; Sgrosso, 1988; Patacca *et al.*, 1992a; Marsella *et al.*, 1995; Menardi Noguera and Rea, 2000). In this study, a paleogeographic model that honours the available stratigraphic and structural data, at least in the sector crossed by the modelled cross-section, has been adopted.

The main units cropping out in the Southern Apennines (Figs. 1 and 3), from bottom to top in the thrust pile which corresponds to a east to west transect in the original paleogeography, are the following: i) the Apulian carbonate platform, ii) the Lagonegro-Molise basins, iii) the Apennine carbonate platform, and iv) the internal oceanic to transitional Liguride-Sicilide basinal domains (internal nappes).

The paleogeography of the region was controlled by Mesozoic extensional tectonics that led to the opening of the Ligurian-Piedmont (or Alpine Tethys) and East-Mediterranean oceanic domains. In the proposed model, the Liguride-Sicilide nappes represent remnants of the Ligurian-Piedmont oceanic domain whereas the Apennine and Apulian carbonate platforms and the intervening Lagonegro-Molise basin developed along the the Adria passive continental margin. The Mesozoic Lagonegro-Molise basin, likely located on thinned continental crust, may have represented the northern marginal part of the East-Mediterranean segment of the Neotethyan ocean (e.g., Ciarapica and Passeri, 2002, Stampfli *et al.*, 2002 and references therein). However, it should be noted that the Apennine and Apulian carbonate platforms and the Lagonegro-Molise basin were originally located on contiguous segments of the same basement belonging to the Apulo-Adriatic plate (Fig. 3).

Figure 3. Southern Apennine stratigraphy



Adopted stratigraphic scheme. The Apennine and the Apulian shallow water carbonate platforms and the intervening Lagonegro-Sannio-Molise basin developed during the Mesozoic rifting and the subsequent passive continental margin evolution of the Apulo-Adriatic plate (modified after Casero *et al.*, 1988).

The complete closure of the Neotethyan domain was achieved in the Southern Apennines in the Late Cretaceous to Early Miocene, following a stage of subduction of oceanic crust (Cello and Mazzoli, 1999). After the overthrusting of the Liguride-Sicilide units onto the Apulo-Adriatic plate Mesozoic passive margin, the sedimentary cover of the passive margin itself was progressively incorporated in the Southern Apennines accretionary prism through a series of thrusting events (e.g., Patacca and Scandone, 2001).

Apulian Carbonate Platform

This units is made up of shallow-water carbonates, 5000 to 7000 m thick, Upper Triassic-Miocene in age (Fig. 3). These carbonates crop out in Apulia region

(Gargano, Murge, and Salento) and represent the pre-orogenic cover of the foreland area (Ricchetti *et al.*, 1988). Upper Messinian and Pliocene deposits stratigraphically overlain the Apulian shallow water carbonates.

The Apulian carbonates rest on the top of Permian volcanoclastic deposits (e.g., Puglia 1 well), or on Ladinian-Carnian carbonate/terrigenous deposits (e.g., Gargano 1 well).

Lagonegro-Sannio and Molise Basinal Units

The characteristics of the Middle Triassic-Early Cretaceous Lagonegro portion of this basinal domain are well established, whereas the nature of the Late Cretaceous-Tertiary section is somehow still debated.

The Lagonegro stratigraphic succession (Fig. 3) is made up of the following four formations which evolve from the fluvial conglomerates and shallow water carbonates of the “Monte Facito” (Middle Triassic), to the “Calcari con Selce” (Late Triassic), “Scisti Silicei” (Jurassic), and “Galestri” (Early Cretaceous) deep water facies (among many others, Scandone, 1967, 1972; Wood, 1981; Miconnet, 1988).

The structural setting of the Lagonegro units has been defined at a regional scale in terms of two superimposed nappes (Scandone, 1972). These nappes have been named respectively Lagonegro type II the upper one (which shows more proximal depositional characteristics), and Lagonegro type I the lower one (with more distal facies). Doubts about this matching between thrust units and sedimentary facies have been raised by Carbone *et al.* (1991) and Mazzoli *et al.* (2001). Regardless, the primary geometry of the Lagonegro units was significantly modified in the Miocene-Pliocene by thrusting, breaching, and out-of-sequence processes which generated complex imbricates (described in detail in a following sections).

Concerning the palinspastic reconstruction of the Lagonegro domains, there is substantial agreement about an original position of the Lagonegro basin between the Apennine and Apulian Platforms. However, it should be noted that an internal provenance of the Lagonegro units has been also proposed by some authors (e.g., Marsella *et al.*, 1995).

The upper portion of the Lagonegro units was detached from its Triassic-Early Cretaceous part and transported farther east. The so-called Sannio Unit likely represent the Late Cretaceous-Early Miocene section of the basin (Carbone *et al.*, 1988; Carbone and Lentini, 1990; Patacca and Scandone, 2007b). Tertiary basinal deposits, completely detached from their original substratum and outcropping along the eastern edge of the Southern Apennines thrust belt, where they are usually named Molise units (Tufillo-Serrapalazzo and Daunia units sensu Patacca *et al.*, 1992a and references therein), could represent the remaing easternmost portion of this basin. The Early Messinian age of the foredeep deposits belonging to the Molise units (Patacca *et al.*, 1992b) documents the original external paleogeographic position of these units (i.e., east of the western carbonate platform and likely at the north-eastern margin of the Lagonegro–Molise basin).

Apennine Carbonate Platform

This unit (Fig. 3) is made up of a thick pile (up to 5000 m) of shallow-water carbonates Late Triassic-Early Miocene in age (Sartoni and Crescenti, 1961; Selli, 1957, 1962). In the area crossed by CROP-04 profile, this paleogeographic domain (also known as Western or Campano-Lucana Platform) includes tidal-flat and protected shelf-lagoon facies (Alburno-Cervati unit), platform-edge (M. Marzano) and slope facies (Monti della Maddalena). The carbonate section is overlain by condensed hemipelagic and siliciclastic deposits related respectively to the flexural sinking of this domain and to the onset of the following foredeep environment (Patacca *et al.*, 1990).

All the thrust sheets derived from Apennine Carbonate Platform are generally detached along an intra-Triassic décollement from their Paleozoic substratum, which has never been reached by exploratory wells.

Internal Nappes

This group of nappes comprises sediments derived from internal domains (Fig. 3) which could be associated with the Ligurian-Piedmont branch of the Neotethyan Ocean. The following units have been recognised.

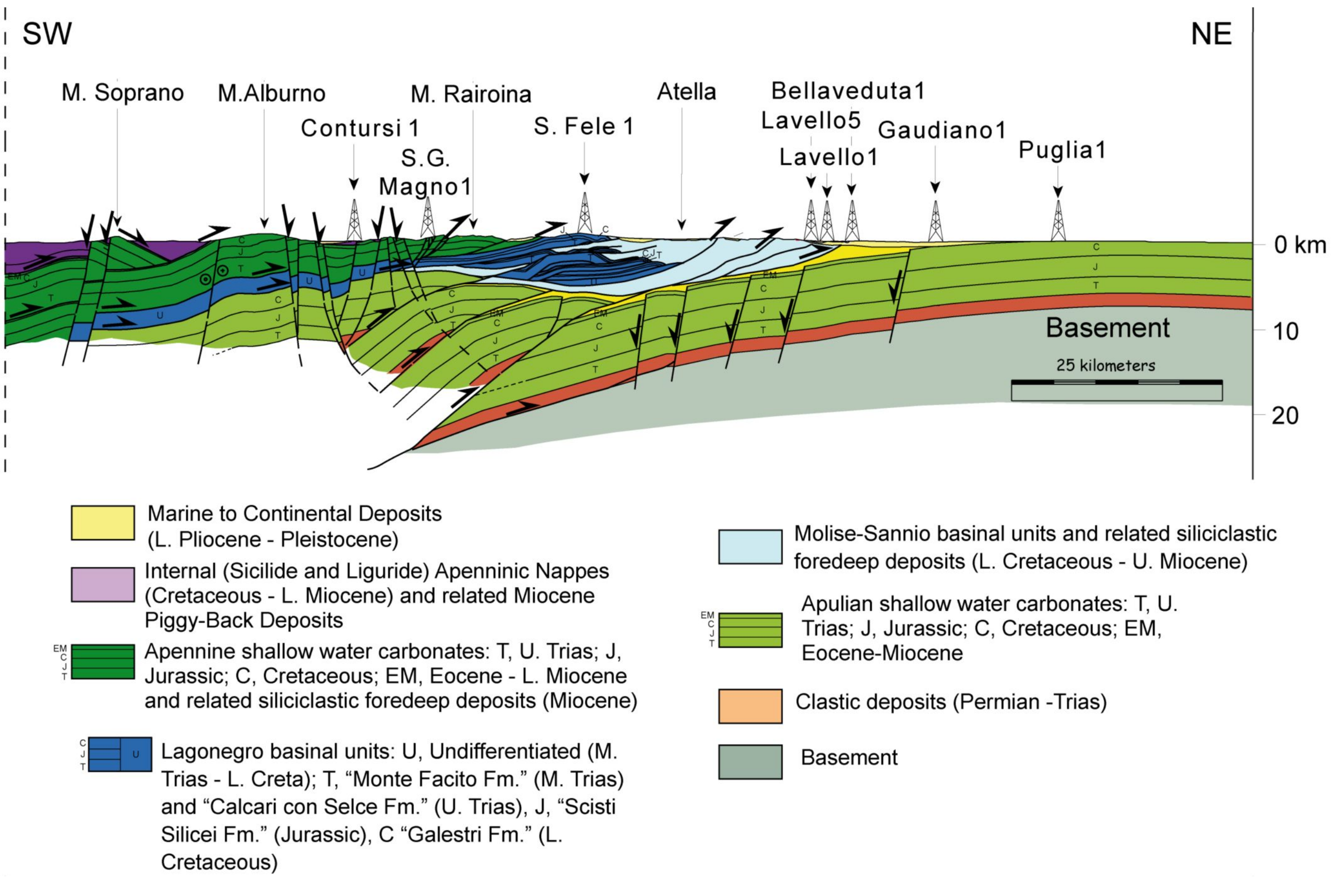
- Liguride units, Early Cretaceous to Early Miocene sequences with incorporated ophiolitic suites. It comprises both the metamorphic Frido Unit and the unmetamorphosed Cilento Unit (Ogniben, 1969; Knott, 1987; Bonardi *et al.*, 1988; Monaco and Tortorici, 1995). The Frido Melange has been interpreted as a part of an accretionary prism built up during the Cretaceous subduction of the Tethys oceanic lithosphere (Knott, 1987, 1994).

- Sicilide units, Late Cretaceous – Early Miocene succession of basinal deposits (Ogniben, 1969). The provenance of the Sicilide units from a basinal domain located west of the Western Platform can be inferred from their geometric position, since the Sicilide units systematically overlie the Alburno-Cervati carbonates from the Cilento area to the high Agri valley. However, an external original position (i.e., east of the Apennine Carbonate Platform) was proposed in other studies (Mostardini and Merlini, 1986; Casero *et al.*, 1988; Pescatore *et al.*, 1988). A discussion on this topic can be found in the work of Menardi Noguera and Rea (2000).

Structural architecture

To illustrate the main structural features of the Southern Apennines, a regional cross-section that cuts across the entire thrust belt-foredeep-foreland system has been modeled. This cross-section is based on the interpretation of the CROP-04 deep seismic reflection profile (Fig. 4), which was acquired, between 1989 and 1990, within the framework of the Italian deep crust exploration project (CROP Project; Scrocca *et al.*, 2003). This profile provides valuable new information on the structure and tectonic evolution of the Southern Apennines. A special issue of the Italian Journal of Geosciences dedicated to the CROP-04 profile collects scientific contributions concerning the geology of the Southern Apennines and the interpretation of this specific profile (Mazzotti *et al.*, 2007 and references therein).

Figure 4. Regional geological cross-section



Regional geological cross-section built along the CROP-04 seismic reflection profile, location in figure 1 (modified after Scrocca *et al.*, 2005 and 2007).

The interpretation of the CROP-04 seismic reflection profile proposed in this paper has been developed combining the results of field surveys, carried along the section trace, and the interpretation of industrial seismic lines and well logs made accessible by the oil industry [see also Scrocca *et al.*, 2005; 2007]. The resulting cross-section can be considered a conservative interpretation of the Southern Apennines structure down to depths of about 10 km (Fig. 4).

Unfortunately, a rigorous structural balancing cannot be properly carried out along the whole cross-section, since the plane strain deformation requirement is not fulfilled in some areas (e.g. strike-slip tectonics or motions out of the plane of section). However, balancing techniques (e.g., key-bed lengths balancing) have been applied where possible in some portions of the cross-section. In this way, the pre-deformational extent of the sedimentary cover (e.g., Apennine platform and Lagonegro basin) or the shortening at top Apulian carbonates horizon have been estimated.

The cross-section will be described starting from its north-eastern edge and then moving towards the Tyrrhenian side. In this description two main structural and geological elements will be considered: the Apulian carbonate platform and the allochthonous units.

Apulian Carbonate Platform

Moving from the foreland toward the foredeep, the top Apulian carbonates horizon (Sella *et al.*, 1988; Nicolai and Gambini, 2007), easily identifiable from seismic reflection and well data (Fig. 5), is characterised by an increasing dip of the regional monocline (Mariotti and Doglioni, 2000) that highlights the flexural geometry of the Apulian Platform (Royden *et al.*, 1987).

Both below the foredeep and in some sectors of the Southern Apennines thrust belt, another deeper, strong reflector can be recognised on seismic reflection data (Roure *et al.*, 1991; Mazzoli *et al.*, 2000). This horizon, generally subparallel to the top of the Apulian carbonate, is interpreted as the bottom of the Apulian carbonates and attributed to the acoustic impedance contrast between the upper Triassic dolomites and the underlain Permo-Triassic clastic deposits (Ricchetti *et al.*, 1988; Mazzoli *et al.*, 2000; Patacca and Scandone 2007a).

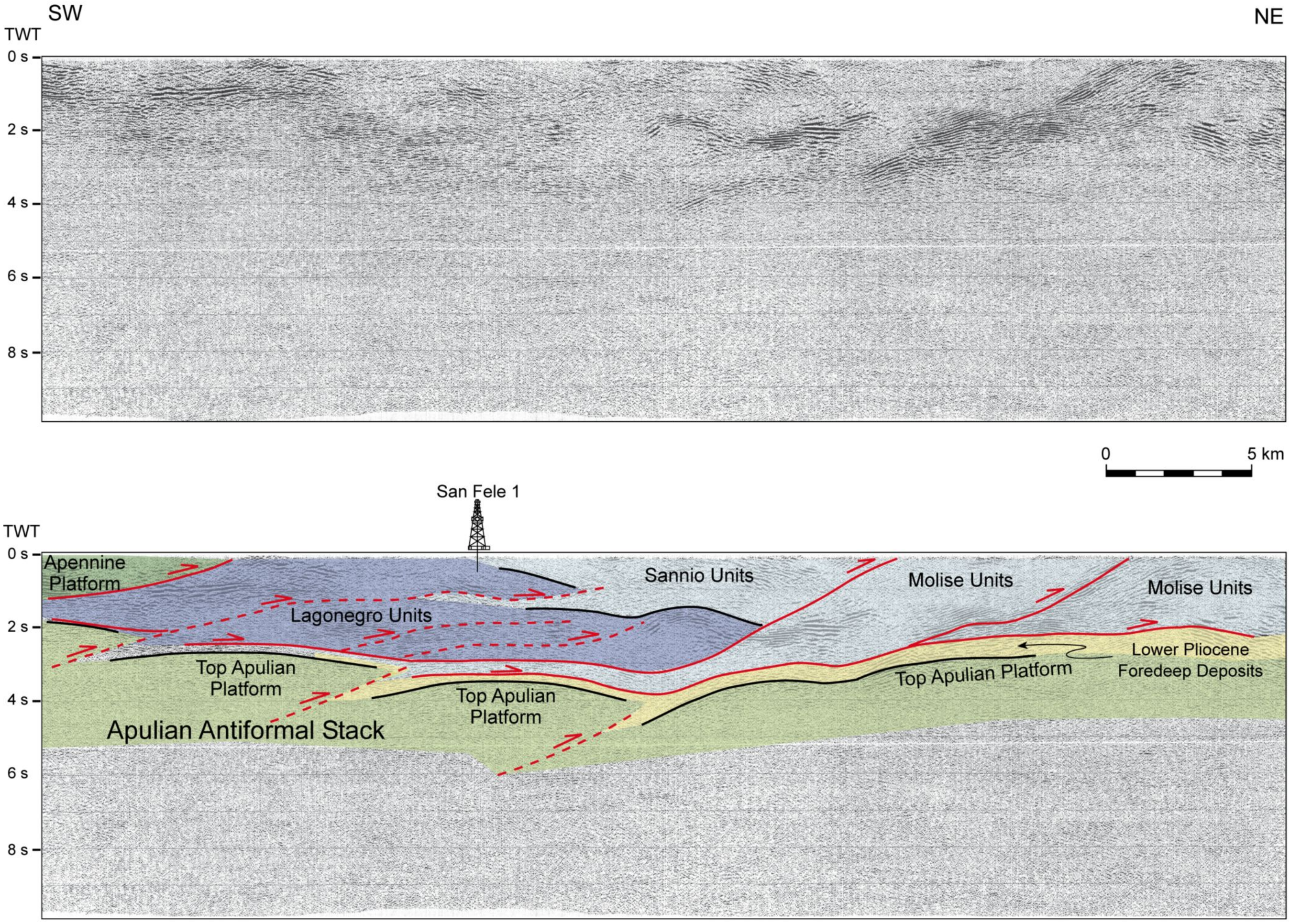
At a regional scale the Apulian Platform shows an almost constant time-interval thickness of about 2.4 s TWT below the foredeep domain. Assuming an average velocity for the Apulian carbonates of about 6000 m/s, this time thickness corresponds in depths to about 7400 m.

In the proposed cross-section the Late Triassic-Miocene Apulian Carbonates have been represented with a simplified stratigraphy, characterised by an average thickness of about 7400 m. A constant thickness of 1500 m has been assumed for the underlying middle Triassic-upper Permian deposits, notwithstanding their recognised syn-rift nature (Merlini *et al.*, 2000; Patacca and Scandone 2007a), due to the lack of information about their lateral regional thickness variations.

Moving westward, along the axial zone of the Southern Apennine thrust belt and below the Lagonegro and Molise allochthonous units (described in the next section), Mesozoic to Tertiary shallow water carbonates were penetrated by several wells. These carbonate deposits, according to their facies and to the age of the stratigraphically overlying foredeep deposits, can be interpreted as portions of the western side of the Apulian carbonate Platform. Available seismic reflection data indicate that these Apulian carbonates are part of imbricated units, forming a buried antiformal stack (Mostardini and Merlini, 1986; Casero *et al.*, 1988; Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000; Patacca and Scandone, 2001). A sole thrust separates the antiformal stack from the relatively undeformed part of the Apulian domain, while another major thrust represent the boundary with the overlying allochthonous units (Figs. 4 and 5).

Unfortunately, as often happens in complex thrust belts, seismic reflection data provide a relatively good definition only of the hanging wall of the thrust units while both the thrust faults and their footwalls, and the deeper horizons (e.g., the bottom Apulian carbonates), remain generally poorly imaged (e.g., Fig. 5). Moreover, the westward extension at depth below the Apennine carbonate platform of the Apulian imbricate units is a matter of debate (e.g., compare interpretations of Menardi Noguera and Rea, 2000 vs. Mazzotti *et al.*, 2000).

Figure 5. Central segment of the CROP-04 seismic profile



Central segment of the CROP-04 seismic profile - Detail of the central part of the CROP-04 seismic profile (location in figure 1) showing the main structural features of the allochthonous units. Horizons and faults are based on the integrated interpretation of well data and industrial seismic reflection profiles available in the area (modified after Scrocca *et al.*, 2007).

In the cross-section presented in figure 4, the structural setting of the Apulian unit has been reconstructed starting from the relatively well constrained hanging wall geometry. Then, thrust faults and related footwalls have been modelled assuming a minimum displacement criterion (see also Scrocca *et al.*, 2005 for details). The main thrusts likely offset both the bottom of the Apulian carbonates and the underlying lower Triassic-upper Permian deposits (e.g., Mazzoli *et al.*, 2000; Shiner *et al.*, 2004).

Below the Apennine platform and Lagonegro thrust sheets, the possible presence of a thrust unit with Apulian affinity has been interpreted following the interpretation of seismic facies on the CROP-04 seismic reflection profile (see also Mazzotti *et al.*, 2000; Scrocca *et al.*, 2007; Patacca and Scandone, 2007a).

Figure 6. Western segment of the CROP-04 seismic profile

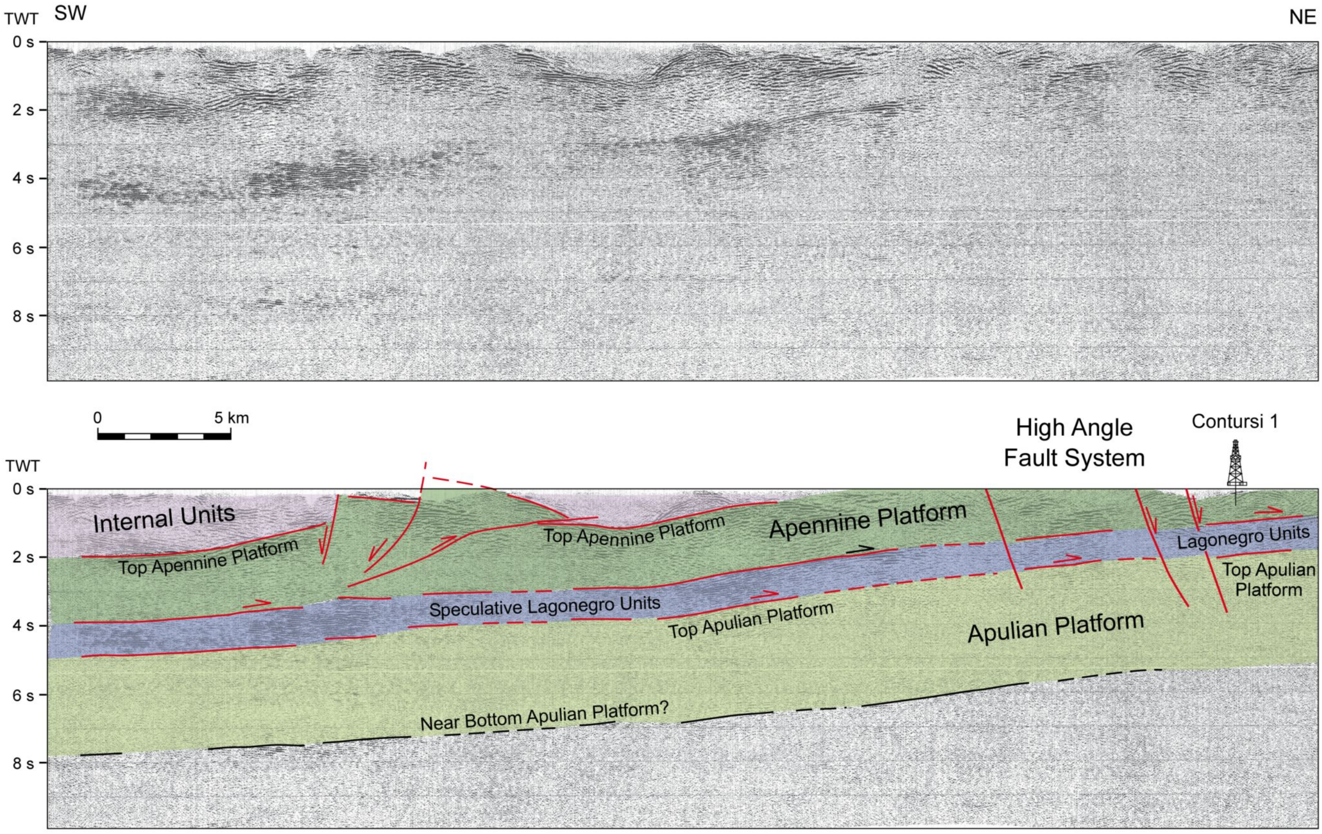


Figure 6. Western segment of the CROP-04 seismic profile - Detail of the western part of the CROP-04 seismic profile (location in figure 1). In this interpretation the Lagonegro units and the Apulian platform extend westward below the Apennine carbonate units (modified after Scrocca *et al.*, 2007).

In this reconstruction, a conservative estimate of about 20 km of shortening (mainly accommodated by thrust faults affecting the top Apulian horizon) has been evaluated, without taking into account pressure solution phenomena possibly affecting the Apulian carbonate. It should be noted that, since the position of the footwall cut-offs for both the top and the bottom Apulian horizon for the two westernmost ramp anticlines is largely unconstrained, larger shortening may not be ruled out.

The onset of contractional deformation in the inner portion of the Apulian domain likely started at the end of the Early Pliocene (e.g., Cello and Mazzoli, 1999) while the main tectonic phases affected this domain during the Late Pliocene-Early Pleistocene (Menardi Noguera and Rea, 2000; Sciamanna *et al.*, 2004).

Allochthonous units

The Tertiary basinal deposits of the Molise Unit (Tufillo-Serrapalazzo and Daunia units sensu Patacca *et al.*, 1992b) are the easternmost and more advanced thrust sheets outcropping in the Southern Apennines thrust belt. The same units represent also the lowest thrust sheets resting above the Early Pliocene deposits overlying the Apulian carbonates (Figs. 4 and 5).

Available subsurface information allows an estimation of the cumulative forward displacement of the allochthonous nappes occurred in the Late Pliocene-Early Pleistocene. A first estimate has been provided by Patacca and Scandone (2001). According to these authors, the nappe advance occurred in two phases (from 3.70 to 3.30 Ma and from1.83 to 1.50 Ma) with at least 30 km of displacement. A second assessment has been proposed by

Sciamanna *et al.* (2004) who have calculated almost 40 km between 3.57 and 0.66 Ma.

Allochthonous units, made up by lithologically monotonous basinal sequences such as the so called “Argille Varicolori” (Varicoloured Shale) outcrop further west. These units, often of unknown age due to the lack of diagnostic fossils, have been attributed to different paleogeographic domains. In the interpretation proposed in figure 4, the large majority of these outcrops have been interpreted as the Late Cretaceous-Early Miocene detached upper portion of the Lagonegro basin, represented by the Sannio Units (Patacca and Scandone, 2007b and references therein).

The Lagonegro units crop out along the axial part of the belt. Available well and seismic reflection data (e.g., Patacca, 2007; Scrocca *et al.*, 2007) document a very complex structural setting, which will be analysed in detail in a following section.

In the south-western part of the cross-section (Fig. 6), the Sicilide units thrust over the Apennine shallow water carbonates, which in turn tectonically overlay the Lagonegro units.

The Apennine carbonate sequence is characterised by a transparent seismic facies, about 1.8-2 s TWT thick that corresponds to about 5000 m in depth, which rests above a very reflective and well stratified seismic facies, less than 1 s TWT thick (Fig. 6). This facies, well known from industrial seismic lines and clearly recognisable also on the western side of the CROP-04 profile, has been interpreted by Menardi Noguera and Rea (2000) as the seismic evidence of a huge slice of Paleozoic basement. However, if well data and the whole seismic image provided by the western side CROP-04 profile are considered, a different interpretation can be proposed (e.g., Mazzotti *et al.*, 2000; Scrocca *et al.*, 2005; Patacca and Scandone, 2007a).

The reflective and well stratified seismic facies has been penetrated by some deep exploration wells (e.g. Contursi 1 well and S. G. Magno 1 wells; Patacca, 2007) where it resulted to be associated to Lagonegro units. Apulian carbonates have been also documented below the Lagonegro units.

Both the stratified seismic facies and the horizon associated to the top Apulian carbonates deepen westward below the Apennine platform thrust sheets as clearly recognisable on the CROP-04 seismic data (Fig. 6). Moreover the CROP-04 profile, due to the higher penetration with respect to industrial seismic reflection data, provides a further support to this interpretation. Across the SW end of the CROP-04 line, at about 8 s TWT, a strong seismic event can be observed that could be interpreted as a near bottom Apulian carbonates reflector.

Several cases of high-angle normal faults, related to both extensional and strike-slip tectonics widely documented by both seismological data and surface geology, can be also observed across the western side of the CROP-04 profile (Figs. 4 and 6). Normal faults NW-SE trending affects Monte Marzano where they reflect the present day extensional tectonic field responsible for the 1980 Irpinian earthquake (Pingue *et al.*, 1988). The Alburno-Cervati massif is delimited on each edge by WNW-ESE sub-vertical, strike-slip, fault systems active in the Late Pliocene (Ascione *et al.*, 1992; Berardi *et al.*, 1996). Also the western side of the M. Soprano ridge is displaced by a major fault system.

Lagonegro Units: kinematic evolution

The Lagonegro units have been drilled by some deep exploration wells (e.g., San Fele 1 and Monte Foi 1 wells; Patacca, 2007), which revealed a complex antiformal stack-type structure.

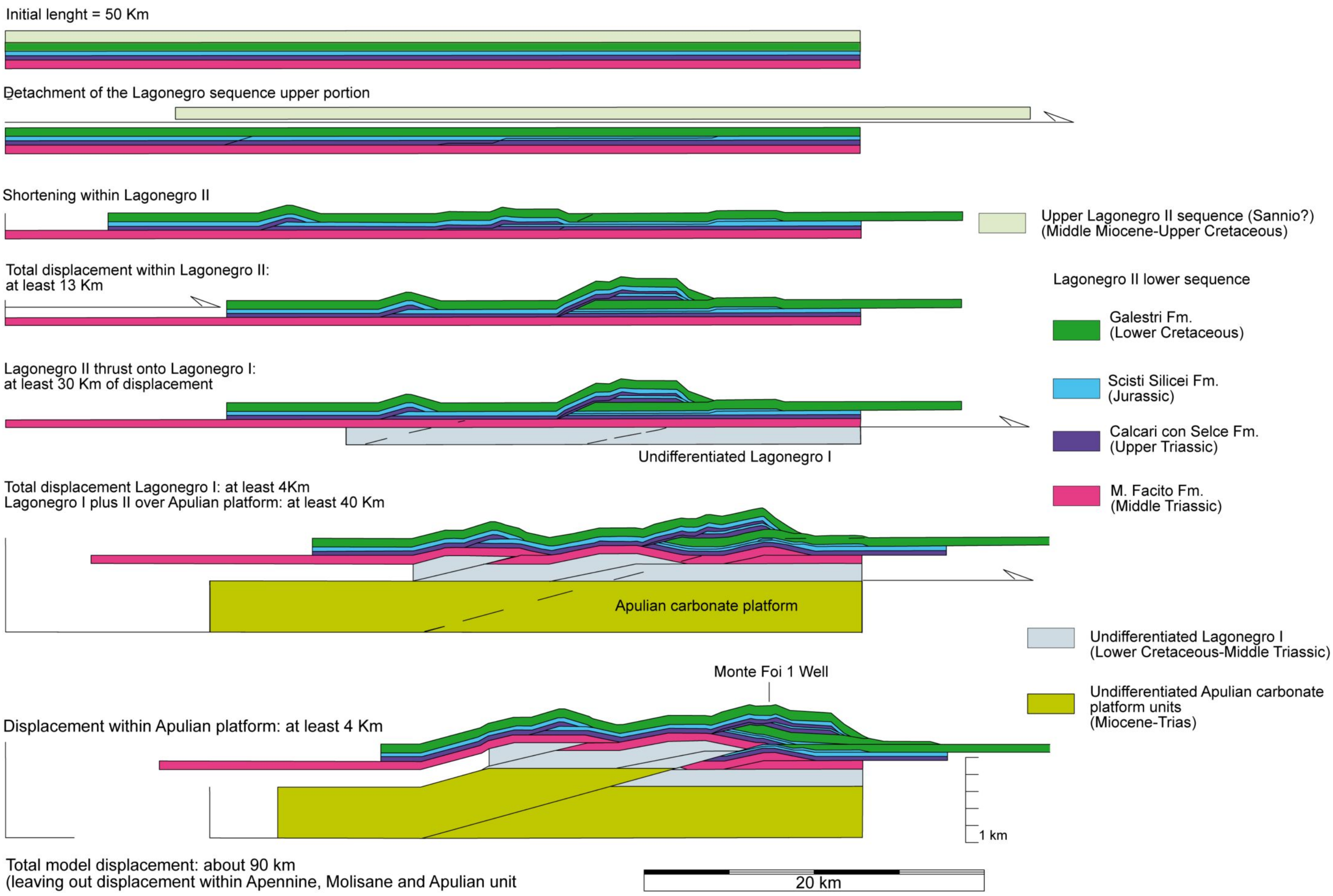
A detailed analysis of the kinematic evolution of the Lagonegro units has been carried in the Monte Foi 1 well area (Fig. 1), where good quality well and seismic data were available (see Scrocca *et al.*, 2007 for further details). In Monte Foi 1 well, several tectonic repetition of formations such as the “Scisti Silicei” and the “Calcari con Selce” have been documented. Sometimes the “Galestri” formation is preserved within this tectonic repetition while no upper Cretaceous - Tertiary units were encountered in this Lagonegro type II structure (Patacca, 2007).

Based on a cross-section intersecting the Monte Foi 1 well, a forward kinematic modelling exercise has been carried out on a slightly simplified version of the interpreted structural setting to test the admissibility of the proposed interpretation (Scrocca *et al.*, 2007). Due to the resolution of seismic and well data, first order features were reproduced by modelling relatively simple ramp-flat geometries. Moreover, for the sake of simplicity, the following assumptions were adopted: i) geological formations have constant thickness; ii) no Tufillo-Serrapalazzo unit were modelled; iii) vertical shear deformation algorithm (volume is conserved during deformation but line lengths may change slightly).

The results of this kinematic forward modelling (Scrocca *et al.*, 2007), bring to light the following deformation history (Fig. 7).

1. The detachment of the Upper Cretaceous-Tertiary cover of the Lagonegro basinal sequence must be a regional and early tectonic process, likely related to the activation of a very efficient intra-Cretaceous detachment (which could corresponds to the Varicoloured shale formation).
2. The development of the tectonic repetitions “Scisti Silicei” - “Calcari con Selce” were an early event caused by the propagation within the Lagonegro type II units of secondary detachments, located at the base of the “Calcari con Selce” and propagating upward with short ramps up to shallower flats at the base of the “Galestri” formation. As a consequence, about 13 km of “Monte Facito” remain without its original Jurassic-Lower Cretaceous cover somewhere on the back of the model (i.e., below the Apennine carbonate platform in the geological cross-section). Ramp segment splaying from the same thrusts at the base of the “Galestri” formation, or breaching thrust ramps propagating from lower detachments, caused the stacking of the tectonic repetition “Scisti Silicei” plus “Calcari con Selce” on top of the “Galestri”.
3. The regional tectonic doubling of the Lagonegro type II over type I was caused by a footwall/hangingwall flat thrust geometry, with at least 40 km of displacement, at any time after (or during) the early Lagonegro II deformation.
4. The Lagonegro units type I and II were already deformed before they overthrusted the Apulian Platform.
5. The final configuration of the Lagonegro antiformal stack is caused by a late stage propagation of at least one main thrust, causing the imbrication of the Apulian carbonate units, which shows out-of-sequence features at the shallower levels but turn out to be a breaching thrust at depth.

Figure 7. Lagonegro units kinematic evolution



Lagonegro units kinematic evolution. This model is based on the structural setting reconstructed for the M. Li Foi area where the M.Foi 1 well has been drilled (modified after Scrocca *et al.*, 2007)

In this model, the minimum length necessary to reproduce the Lagonegro II structural setting is of at least 50 km. Other 40 km should be added to the initial model to take into account the regional overthrusting of the Lagonegro II over the Lagonegro I units. Consequently, to honour the available data in the M. Foi area, the minimum total width of the Lagonegro basin is of at least 90 km. Moreover, as suggested by the combined interpretation of wells data and CROP-04 seismic profile (fig. 4), about 30-40 km of undifferentiated Lagonegro units should be buried below the Apennine units. As a result, in the segment of the Southern Apennines crossed by the CROP-04 profile, the total width of the Lagonegro basinal domain could be estimated in about 125 km.

Missing Basement

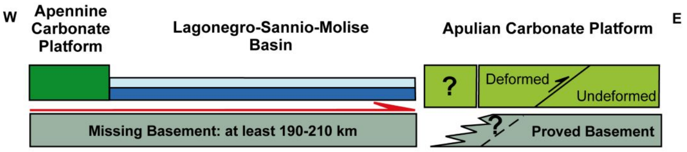
Apart from the controversial situation described below the M. Alburno massif (i.e., interpretations of Menardi Noguera and Rea, 2000 vs. Mazzotti *et al.*, 2000), there is a wide agreement that the sedimentary covers belonging to the Apennine Carbonate Platform and to the Lagonegro-Molise basin are completely detached from their original basement.

To quantitatively assess the amount of missing crystalline basement, the pre-deformational width of the Apennine platform and of the Lagonegro basin has been estimated assuming that an equivalent amount of crystalline basement was originally situated below these domains (Scrocca *et al.*, 2005)

To get this result, line lengths of key-bed, which show little penetrative deformation and preserved hanging wall and footwall cutoffs, have been computed for the Apennine Carbonate Platform (i.e., top Jurassic) and the Lagonegro basinal units (i.e., top Late Triassic corresponding to the top of the" Calcari con Selce" Formation) on the cross-section proposed in figure 4.

This simplified approach is obviously affected by some approximation (e.g., pressure solution phenomena, strike slip tectonics or polyphase deformation have not been considered) but it provides a useful first order estimate. The resulting total length of the missing crystalline basement could be estimated in the range of 190-210 km (Fig. 8), with about 70-80 km originally located below the Apennine carbonate platform and 120-130 km below the Lagonegro basin (in agreement with the result of the detailed tectonic modelling of the Lagonegro units).

Figure 8. Missing basement



Available well and seismic data show that the sedimentary covers belonging to the Apennine Carbonate Platform and to the Lagonegro-Molise basin are completely detached from their original basement. The amount of missing crystalline basement, originally located below these domains, has been approximately evaluated along our regional cross-section applying key-bed balancing techniques to derive the pre-deformational width of the sedimentary cover. By means of key-bed balancing techniques applied to the regional cross section, the amount of missing crystalline basement is estimated to be about 190-210 km (modified after Scrocca *et al.*, 2005).

This piece of evidence implies that during the eastward roll-back of the subduction hinge the sedimentary covers of both the Apennine Carbonate Platform and the Lagonegro-Molise basin have been off-scraped from the subducting Apulo-Adriatic lithosphere (e.g., Roure *et al.*, 1991; Doglioni *et al.*, 1996]. Moreover, the same tectonic process, together with the absence of documented basement slice in the accretionary prism, requires that the crystalline basement originally underlying these sedimentary cover must have disappeared in the subduction zone.

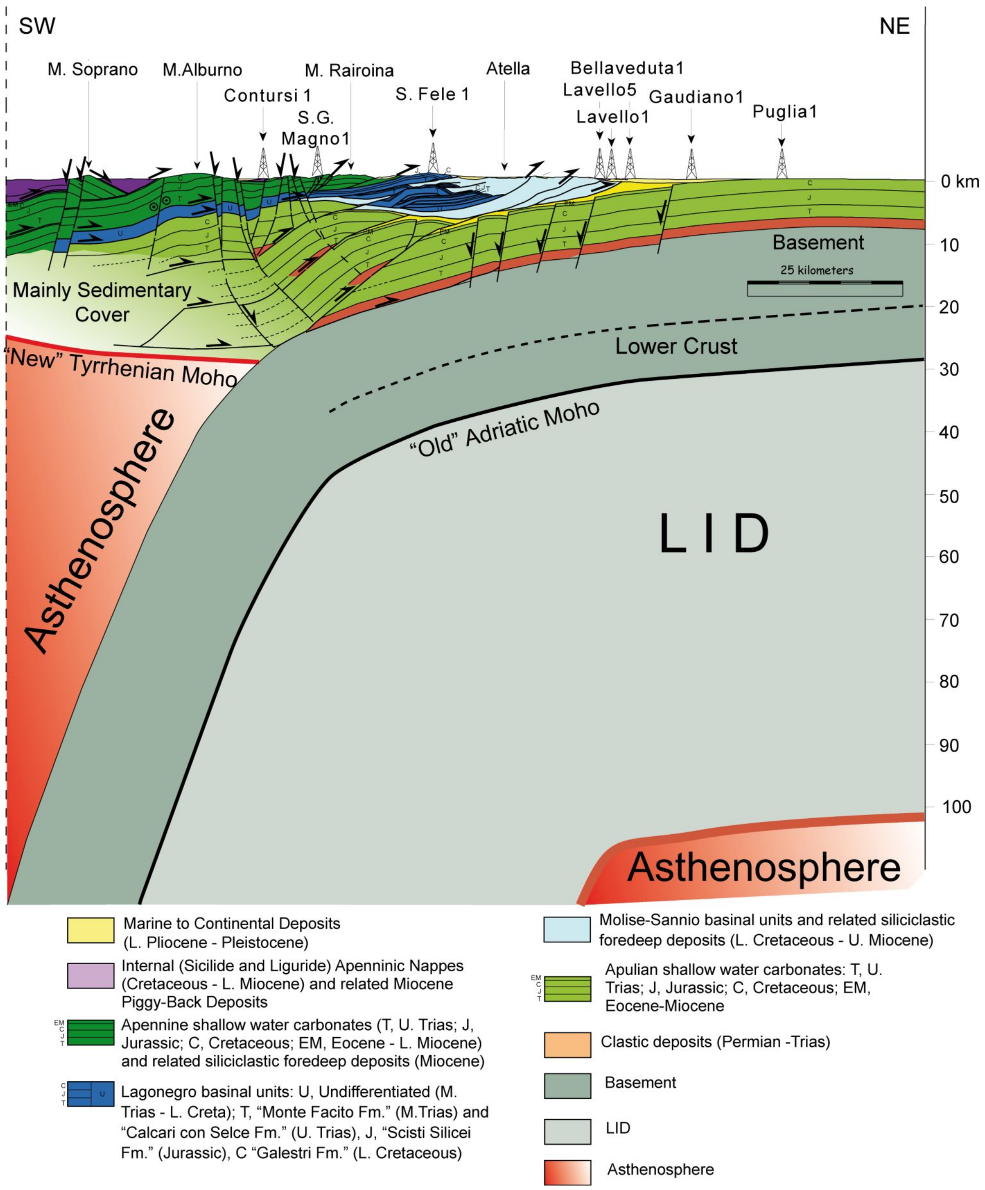
Geodynamic setting

To illustrate the proposed geodynamic model of the Southern Apennines, the geological cross-section has been framed in the large scale lithospheric setting suggested by the available geophysical and geochemical data.

Although geodynamic interpretations that do not consider the subduction below the Apennines have been proposed, in this paper only a subduction model will be considered. Indeed, the simple and indisputable observation that about 190-210 km of crystalline basement (the former substratum of allochthonous units) are missing strongly support the westward subduction of the Apulo-Adriatic continental lithosphere under the Southern Apennines, as also suggested by the several independent geophysical datasets. The proposed large scale section (Fig. 9), is constrained with the following geophysical information.

The geometry of the Moho and of the lithosphere-asthenosphere boundary is based on passive seismological studies (Panza *et al.* 1992; Nicolich and Dal Piaz 1992; Scarascia *et al.* 1994; Nicolich, 2001; Pontevivo and Panza, 2002). The Apulian crust is about 30 km thick in the foreland. The Apulo-Adriatic Moho dips toward SW, at least down to a depth of about 50 km below the Tyrrhenian coast. Along the Tyrrhenian Sea, a different and shallower Moho (named “Tyrrhenian”) has been recognised at depths of 25-30 km.

Figure 9. Lithospheric transect across the Southern Apennines



Lithospheric transect (location in figure 1) across the Southern Apennines showing: i) the flexure of the westward subducting Apulian lithosphere, and ii) the hot mantle wedge underlying a new "young" and hot Moho along the western side of transect. Although available geological and geophysical information cannot resolve the existing uncertainties about the deep structure of the Southern Apennines, an integrated analysis of documented tectonic, geophysical and geochemical features shows that a thin-skinned model is generally more consistent with the available data (modified after Carminati *et al.*, 2004 and Scrocca *et al.*, 2005).

The possible location of the slab below the Southern Apennines is constrained by mantle tomography models (Spakman, 1990; Spakman *et al.*, 1993; Amato *et al.*, 1993; Piromallo and Morelli, 1997; Amato *et al.*, 1998; Lucente *et al.*, 1999). Weaker high velocity anomalies detected on some of these models and the absence of sub-crustal seismicity created the latitude for interpretations speculating slabless window (Amato *et al.*, 1993; Lucente *et al.*, 1999) or detached slab (Spakman, 1990; Spakman *et al.*,1993) below the Southern Apennines. However, more recent and detailed tomographic studies focused on the Southern Apennines (e.g., De Gori *et al.*, 2001) highlighted the presence of an almost continuous sub-vertical high velocity body, extending from depths of 65 km down to 285 km. If this is the case, the absence of subcrustal seismicity could be explained with the continental composition of the subducting Adriatic lithosphere (Carminati *et al.*, 2002), which is expected to have ductile rather than brittle behaviour (and to accommodate deformation aseismically rather than seismically).

The location of the proposed Apennine slab is consistent with the occurrence of positive Bouguer anomalies (up to 120 mGal or more; Consiglio Nazionale delle Ricerche, 1992) and very high heat-flow values (up to 140 mW/m^2 or more; Della Vedova *et al.* 2001) along the Tyrrhenian margin and in the adjacent Tyrrhenian Sea. The occurrence of hot asthenospheric material at relatively shallow depth below the western portion of the Southern Apennines is also coherent with the results of the analysis of the shear waves attenuation (Mele *et al.*, 1997) and of helium isotope ratios together with the amount of released gas (Italiano *et al.*, 2000).

The main features that should be noted in the proposed lithospheric section are (Fig. 9): i) the flexure of the subducting Apulian lithosphere, with the slab top deeper than 100 km below the Tyrrhenian coastline; and ii) the presence of a hot mantle wedge underlying a new "young" and hot Moho in the western side of the accretionary prism.

It is generally agreed that the tectonic evolution of the Southern Apennines has been essentially controlled by the flexure-hinge retreat of the westward subduction of the Apulo-Adriatic continental lithosphere (among many other, Malinverno and Ryan, 1986; Patacca *et al.*, 1990; Doglioni, 1991; Doglioni *et al.*, 1996, 1999, 2007). In this subduction retreat model, the retreating slab is replaced by asthenospheric materials in a context of no (or very low) plate convergence. Accordingly, the Tyrrhenian Moho can be considered as a newly forming crust-asthenosphere boundary associated with the well known high heat flow characterising the Tyrrhenian area and the western side of the Italian peninsula. The genesis of the Adriatic Moho, which generally shows quite low heat flow, can be associated with the Mesozoic rifting stages.

The proposed geodynamic model envisages the subduction of a large part of the continental crust associated with the lithospheric mantle of the Apulo-Adriatic plate. The subduction of continental crustal rocks, although often considered an unlikely tectonic process, is suggested by geochemical signatures in the calkalcaline magmas of the volcanic arc (Peccerillo, 1985; Serri *et al.*, 1993) and by the already stated amount of missing basement.

Following the model originally proposed by Doglioni, (1991), the main mechanism which drives the Apennine subduction could be considered the westward relative motion of lithosphere relative to the mantle. The continental crust is interpreted to subduct in response to the eastward push of the asthenosphere rather than to the negative buoyancy of the slab (slab pull). The upper boundary for the subducting plate is defined by the main active detachment, which plunges steadily westward following the lower plate flexure.

In this model, the shear between the down-going and retreating lithosphere and the eastward flow of the asthenosphere compensating the subduction rollback is transferred upward to the accretionary prism, where it is responsible for the off-scraping of the sedimentary cover from the subducting lithosphere (Doglioni *et al.*, 1999).

Thin-skinned versus thick-skinned models

As already discussed in the previous sections, the available data support the concept that the allochthonous units (e.g. Apennine carbonate platform and Lagonegro-Molise basin) are characterised by a thin-skinned tectonic style. On the contrary the deep structure of the buried Apulian antiformal stack is not sufficiently constrained by the available geological and the geophysical data, so that both thin- and thick-skinned could be put forward.

Although the available information cannot resolve the existing uncertainties about the deep structure of the Southern Apennines, it is at least possible to compare the main tectonic and geodynamic implications of alternative thin-skinned and thick-skinned interpretations.

This task has been carried out by Scrocca *et al.* (2005), by developing both a thin- and a thick-skinned model on the base of the same conservative cross section presented in figure 4.

In the thick-skinned model the Apulian crystalline basement is deeply involved with the development of three major slices and the estimated shortening in the Apulian carbonate units corresponds to about 20 km. In the thin-skinned model basement is not involved and total shortening of the buried Apulian thrust sheets is assessed to be not less than 90 km.

These alternative models, which must be regarded as two end-members, has been cross-checked against well documented tectonic, geophysical and geochemical features of the Southern Apennines. The main results of this analysis are the following (see details in Scrocca *et al.*, 2005).

It should be noted that the thick-skinned model necessarily requires a transition from thin- to thick-skinned tectonic style, since the available data document a thin-skinned deformation during the Middle Miocene-Early Pliocene tectonic accretion of the allochthonous units. This transition is implicitly or explicitly assumed in several published papers proposing a thick-skinned interpretation for the buried Apulian thrust units (e.g., Casero *et al.*, 1988; Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000; Butler *et al.*, 2004; Sciamanna *et al.*, 2004; Speranza and Chiappini, 2002).

The post- Early Pliocene transition from a thin- to a thick-skinned tectonic style should have occurred through a crustal down-section propagation of the main detachment during the contractional deformation of the Apulian domain with the development of basement slices tens of kilometres thick. The modified slab geometry required by the emplacement of the basement slices no longer fit the crustal and lithospheric setting suggested by the available geophysical constraints (e.g., slab needs to be shifted more than 50 km westward and no more space is left for the asthenospheric wedge). A thin-skinned interpretation can be instead easily framed in the large scale geodynamic setting constrained by the available geophysical data.

Following the estimated proposed by Scrocca *et al.* (2005), the thick-skinned model should have induced approximate “uplift of rock” rates in excess of 1.7 mm/a. This value is significantly larger than the about 0.5-0.7 mm/a measured and estimated (for the last 2 Ma), in the axial zone of chain, using both geomorphological observations and stratigraphical/structural data (Amato and Cinque, 1999; Amato, 2000; Schiattarella *et al.*, 2003, 2006; Ferranti and Oldow, 2005). On the contrary in a thin-skinned model, the Southern Apennines accretionary wedge and the related induced topography developed horizontally moving as a fast wave towards the east, rather than growing vertically, at rates of at least 10-30 mm/a (Patacca *et al.*, 1990; Gueguen *et al.*, 1998). The average expected uplift rates are generally lower than 1 mm/a (Doglioni *et al.*, 1999), with peak values reached only for a short time span in which the tectonic wave crosses an area.

The low displacement in Apulian carbonates implies by the thick-skinned interpretations (about 20 km) cannot explain the Late Pliocene-Early Pleistocene forward motion of the allochthonous nappes, estimated in at least 30-40 km (Patacca and Scandone, 2001; Sciamanna *et al.*, 2004). This discrepancy has been interpreted as evidence that gravitational instabilities within the allochthonous wedge were likely to have substantially contributed to the tectonic advance of the allochthonous nappes by a process of extension linked with thin-skinned thrusting (e.g., Schiattarella *et al.*, 2006; Mazzoli *et al.*, 2008 and references therein).

However, the low displacement hypothesis also conflicts with the observed maturity trends in the Apulian carbonates inferred from vitrinite reflectance data. In particular, the results of a 2D thermal and geochemical modelling (Sciamanna *et al.*, 2004), performed on geological profile cutting across the major oil discoveries located in the Val d’Agri, revealed that the few kilometres of displacement assumed between the innermost Apulian thrust sheets in this thick-skinned interpretation are incompatible with the observed differences in maturity trends.

In conclusion, the thin-skinned model, with displacements among the Apulian thrust sheets in the order of several tens of kilometres, seems to be a preferable tectonic interpretation since it could coherently explain both the observed maturity trends in the Apulian carbonates and the Late Pliocene-Early Pleistocene front advance of the allochthonous nappes.

Conclusions

The Southern Apennines thrust belt developed during Neogene and Quaternary times along the eastward-retreating west-directed subduction of the Apulo-Adriatic lithosphere. The development of the Southern Apennines accretionary prism occurred through the off-scraping and incorporation at the subduction zone of the Meso-Cenozoic sedimentary covers (essentially pelagic units and shallow water carbonates) located along the Apulo-Adriatic passive margin, and associated active margin deposits. Since the Early Miocene, the accretionary prism migrated from west to east. Contractional deformations were followed by coeval extensional faulting which, progressively, cross-cut the thrust pile.

The main geological units incorporated in the Southern Apennines are from bottom to top in the thrust pile that corresponds to an east-to-west transect in the original paleogeography: i) the Apulian carbonate platform, ii) the Lagonegro-Molise basins, iii) the Apennine carbonate platform, and iv) the internal oceanic to transitional Liguride-Sicilide basinal domains (internal nappes).

The unquestionable evidence that about 190-210 km of crystalline basement (the former substratum of the allochthonous units) are missing, strongly supports the westward subduction of the Apulo-Adriatic continental lithosphere under the Southern Apennines. This geodynamic interpretation is also corroborated by several independent geophysical datasets.

Notwithstanding the wealth of subsurface data provided by the intense hydrocarbon exploration and the results of good quality structural and stratigraphic researches, the Southern Apennines structural setting could be effectively constrained only to a depth of about 10 km. The deeper setting is indeed still a matter of scientific debate. The two major unresolved issues regard: i) the shortening within the Apulian carbonate platform units, and ii) the degree of involvement of the Apulian crystalline basement. As a result both thin- and thick-skinned interpretation have been proposed.

However, if both thin- and thick-skinned are cross-checked against well documented tectonic, geophysical and geochemical features it emerges that the thin-skinned model is generally more consistent with the available data. Although it remains possible that the upper few kilometres of the Apulian basement could have been involved in thrusting, a thick-skinned interpretation (characterised by the development of basement slices tens of kilometres thick) is unable to coherently explain the overall geodynamic setting, the estimated "uplift of rock" rates, the observed maturity trends in the Apulian carbonates, and the Late Pliocene-Early Pleistocene front advance of the allochthonous nappes.

In the preferred thin-skinned model, about 90 km of shortening can be attributed to the Apulian thrust units. The total shortening of the allochthonous units (i.e., Apennine and Apulian Carbonate platforms and Lagonegro basin) is estimated to be greater than 280-300 km, a value relatively consistent with the length of the slab subducted beneath the Southern Apennines imaged by seismic tomography.

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