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Collisional and postcollisional tectonics of the Apenninic-Maghrebian orogen (southern Italy)

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ABSTRACT

Geological analysis of geophysical data obtained by the interpretation of crustal profiles indicates that in the central Mediterranean region the following structural domains can be distinguished: the foreland domains, an orogenic belt, and the Corsica-Sardinia block. The foreland domains are represented by two continental blocks, the Apulian block to the north and the Pelagian block to the south, belonging respectively to the Adria and to the Africa plates, separated by the oceanic crust of the Ionian Sea. The orogenic belt is located between two oceanic crusts: the old Ionian crust, at the present time subducting beneath the Calabrian arc, and the new crust of the Tyrrhenian Sea. The orogenic belt is represented by a multilayer allochthonous edifice composed of the Calabride chain, which tectonically overlies the so-called Apenninic-Maghrebian chain, which in turn is overthrust onto the upper Miocene and Pliocene top levels of a deep-seated thrust system that originated from the deformation of the innermost carbonates of the Apulian and Pelagian blocks (the external thrust system). The Calabride chain is composed of crystalline nappes originating, since the Eo-Oligocene, from the delaminated margin of the Europe plate. The Apenninic-Maghrebian chain tectonic units derive from the orogenic transport during Oligo-Miocene times of sedimentary sequences deposited in paleogeographic domains located between the Europe and the Afro-Adria plates. These units are composed of meso-Cenozoic shallow-water carbonate successions detached from a continental type of crustal sector named here the Panormide-Apenninic block. This is now recognizable by means of seismic lines shot in the Tyrrhenian off-shore of the southern Apennines and northern Sicily. The meso-Cenozoic basinal units that constitute the Apenninic-Maghrebian chain can be distinguished into two main groups of sequences, originally located on oceanic crusts separated by the Panormide-Apenninic crust: the external ones (Ionides) related to an original basin belonging to part of the Ionian paleo-basin involved in the orogenesis (Lagonegro, Imerese, Sicanian, and Monte Judica units) and the internal ones ascribed to the Alpine Tethys (Liguride-Sicilide units).

The previously described allochthonous edifice is characterized by thin-skinned tectonics and represents a roof thrust system resting on the external thrust system,

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which derived from thick-skinned tectonics that produced folds and reverse faults with relatively moderate horizontal displacements. The external thrust system developed from late Miocene times, contemporaneously with the opening of the Tyrrhenian basin, and is named the Apulian thrust system in southern Italy and the Pelagian-Sicilian thrust belt in Sicily.

The crustal sections of the CROP project (Deep Seismic Exploration in the Central Mediterranean and Italy) allow us to distinguish the thickness and distribution of the crusts in this area of the Mediterranean Sea, and they confirm that the foreland continental blocks, the Apulian and the Pelagian blocks, are separated by the Ionian oceanic crust. Both the foreland blocks extend below the orogenic belt, reaching the Tyrrhenian margins, with a gradual thinning and a transition to a Paleo-Ionian slab, probably not active at present time, from which the Ionides detached and overrode the external thrust system. The seismogeological data indicate the presence of a continental block, original basement of the Panormide-Apenninic platforms, that took part in the closure of the sectors of the Paleo-Ionian Sea interposed between the Panormide-Apenninic crust and the Pelagian and Apulian blocks. At the present time, it is colliding with the foreland blocks. Thus, this has been identified as collisional crust. The geologic evidence of this collisional stage is manifested in the northwest-southeast-oriented South Tyrrhenian system, which is characterized by dextral faults affecting both off-shore and on-shore areas of Sicily. A mirrorlike sinistral fault system occurs in the southern Apennines. Interpretative seismic reprocessing has permitted clear seismic imaging of the subducted Ionian slab. The distribution of the earthquakes transversally and longitudinally indicates that the slab is narrowing in a vertical direction; thus, at present, the active slab is limited to a short segment between northeastern Sicily (the Vulcano line) and southern Calabria (the Catanzaro line). To the west and to the northeast of these lines, a collisional setting can be recognized.

The geological and geophysical data and the volcanological characteristics of the study area permit us to restore the paleogeographic and paleotectonic setting and have allowed us to recognize three orogenic stages: the Eo-Alpine, which originated during Cretaceous–Eocene times but is less evident in the study area; the Balearic stage (late Oligocene–early Miocene), in which the Corsica-Sardinia block collided with the Adria-Africa margins with thrusting of the Alpine Tethydes over Panormide units; and the Tyrrhenian stage (middle Miocene to present), when the onset of the Tyrrhenian back-arc basin occurred and the collisional crust followed the Ionian slab retreat, closing the interposed basin with tectonic transport of the Ionian ocean cover (the Ionides) over the foreland blocks.

Keywords: southern Apennines, Sicily, Calabrian arc, Tyrrhenian basin, geodynamics, thrust tectonics

INTRODUCTION

The present-day tectonic setting of the southern Apennines–Calabrian arc–Sicily orogenic system is the product of a complicated geodynamic evolution in which a fundamental role is played by the distribution of crustal components. The orogenic belt is located between an old oceanic crust, the Ionian basin, which has been partially consumed, and a new oceanic crust, the abyssal plane of the Tyrrhenian basin. The CROP-Mare project, using seismic lines, recognized a continental crust in the circum-Tyrrhenian margins associated with migrated tectonic stacks that were colliding with the continental blocks of the Africa and Adria plates. This recognition is key for the correct understanding of the current tectonics and geodynamics of the central Mediterranean area (Lentini et al., 1996, 2002; Finetti et al., 2005a,b).

The regional geological data, obtained from decades of field studies and analyses and integrated with volcanological as well as geophysical data, provide geodynamic constraints that permit us to propose a new model. Following the earlier tectonic models, the geodynamic setting of the Tyrrhenian-Apenninic system has traditionally been thought to have resulted from a complicated collisional process between the Africa and the Eurasia plates, active since 65 Ma (Dercourt et al., 1986; Dewey et al., 1989; Patacca et al., 1990). During late Oligocene–early Miocene times the eastward retreat of the subducting Alpine-Tethyan lithosphere produced rifting of the European crust and led to the opening of the western Mediterranean (the Balearic basin) with a counterclockwise rotation of the Corsica-Sardinia block (Malinverno and Ryan, 1986; Faccenna et al., 1996).

A wider knowledge of the southern Apennines geological features has led many authors to propose various models and interpretations of their tectonic evolution (Ogniben, 1969; Scandone, 1972; D'Argenio et al., 1973; Pescatore et al., 1988; Ben Avraham et al., 1990; Marsella et al., 1992; Monaco et al., 1998; Patacca and Scandone, 2001; Lentini et al., 2002). Each model highlights some particular aspects but neglects others and often lacks testing in the field. In some cases, the interpretations are in contrast with the structural and stratigraphic evidence. Lentini et al. (2002) recognize two tectonic wedges in the southern Apennines, characterized by compressive deformation tied to a thin-skinned tectonic context. The more ancient accretionary wedge (late Oligocene–early Miocene) is connected with the subduction of the Tethyan oceanic crust, the origin of the Liguride-Sicilide nappes. This subduction process stopped at the time of collision between the European margin and a continental crust (the Maghrebian crust), recognized from seismic lines, originally located between the Tethys and the Ionian oceanic crusts. The second orogenic phase took place from middle Miocene times with the opening of the present-day back-arc Tyrrhenian basin. This led, at the end of Pliocene, to the comsumption of part of the Paleo-Ionian crust and the collision of the "Maghrebian" continental crust with the Africa-Adria continental crusts (Finetti et al., 2005a,b).

For decades, many papers have emphasized the geological analogies between Sicily and the southern Apennines (Ogniben, 1960, 1969). Many authors have described the southern Apenninic arc or the Sicilian orogenic belt as the result of a collision between the European and African crusts. As described by Parotto and Praturlon (2004, and references therein), the southern Apennines–Calabria–Sicily arc developed through the deformation of two major paleogeographic domains: a Neo-Tethyan Sea and an external continental passive margin, progressively incorporated into the chain. Extensive information about the geology of this area can be found in Bianchi et al. (1987), Bello et al. (2000), Catalano et al. (2000), and Patacca and Scandone (2004).

The southern Apenninic arc is composed of two components: the southern Apennines wing to the north and the Calabrian arc to the south. Patacca and Scandone (1989) suggest that the different curvature of the two arcs is an expression of a nonuniform retreat of the subducting slab. But from the geodynamic point of view, the true arc is the Calabrian arc, which is represented by crustal fragments overriding the Ionian oceanic crust together with a back-arc basin and a volcanic arc (the Aeolian islands). The wings at the extremities of the arc are two arcuate-shaped belts, the southern Apennines and Sicily, which originated from a collisional stage between the continental backbone of the Apenninic-Maghrebian chain and the Afro-Adriatic continental crusts. From Quaternary times, the more pronounced slab retreat beneath the Calabrian arc with respect to the southern Apennines and Sicily produced a tearing of the crust through two transfer fault systems: the Vulcano line to the west and the Catanzaro line to the east (Lentini et al., 2002; Guarnieri and Carbone, 2003). These two lines (Fig. 1) accommodate the differential movements between the Sicilian thrust belt and the southern Apennines thrust system in a collisional setting and also the still subducting Ionian slab beneath the southernmost segment of the Calabrian arc.

In the central Mediterranean region (Fig. 1), some structural domains have been distinguished: the foreland domain, the orogenic domain, and the hinterland domain (Ben Avraham et al., 1990; Lentini et al., 1994, 1995a, b; Finetti et al., 1996). The foreland domain includes the currently undeformed continental areas consisting of the Apulian block, the Pelagian block, and the Ionian basin. The Apulian block has been separated since the late Paleozoic from the Pelagian block of the Africa plate by the oceanic crust of the Ionian basin. The orogenic domain is composed of three superimposed tectonic belts, the external thrust system, the Apenninic-Maghrebian chain , and the Calabride chain. The external thrust system has been generated by the detachment of the internal sedimentary cover of the flexured sector of the continental foreland, with the Apenninic-Maghrebian chain that originated by means of the imbrication of the sedimentary sequences belonging both to the oceanic crust-type sectors (the Tethys and Ionian basins) and to the continental-type crust sectors (the Panormide-Apenninic carbonate platforms). The Calabride chain is thought to be the product of the delamination of the European margin or partially that of the deformation of an Austroalpine belt.

The peculiarity of the orogenic belt in the southern Apennines as well as in Sicily mainly lies in a general duplex geometry (Fig. 2). The roof thrust system, some thousand meters thick, is composed of the allochthonous units of the Apenninic-Maghrebian chain, while the floor thrust is represented by the external thrust system. The latter corresponds to the so-called Apulian chain of Carbone and Lentini (1988, 1990), or to the Apulian thrust system (Finetti et al., 2005a) in the southern Apennines, and to the Pelagian-Sicilian thrust belt in Sicily (Finetti et al., 2005b). It is composed of more or less rooted carbonate units derived from the internal edge of the Adria plate and of the Africa plate, respectively. The Apulian thrust system consists of a buried imbricated fan (Casero et al., 1988; Lentini et al., 1996) belonging to the flexured carbonates of the Apulian block. The hinterland domain is represented by the Corsica-Sardinia block and the Tyrrhenian basin. The latter is characterized by an oceanic crust. Opening started in Serravallian time, as determined from a study of the Tyrrhenian margin of Sicily (Lentini et al., 1995a,b).

This article commences with a general description of the tectonostratigraphy both of the southern Apennines and of the Sicily orogen, arranged so as to hightlight the considerable

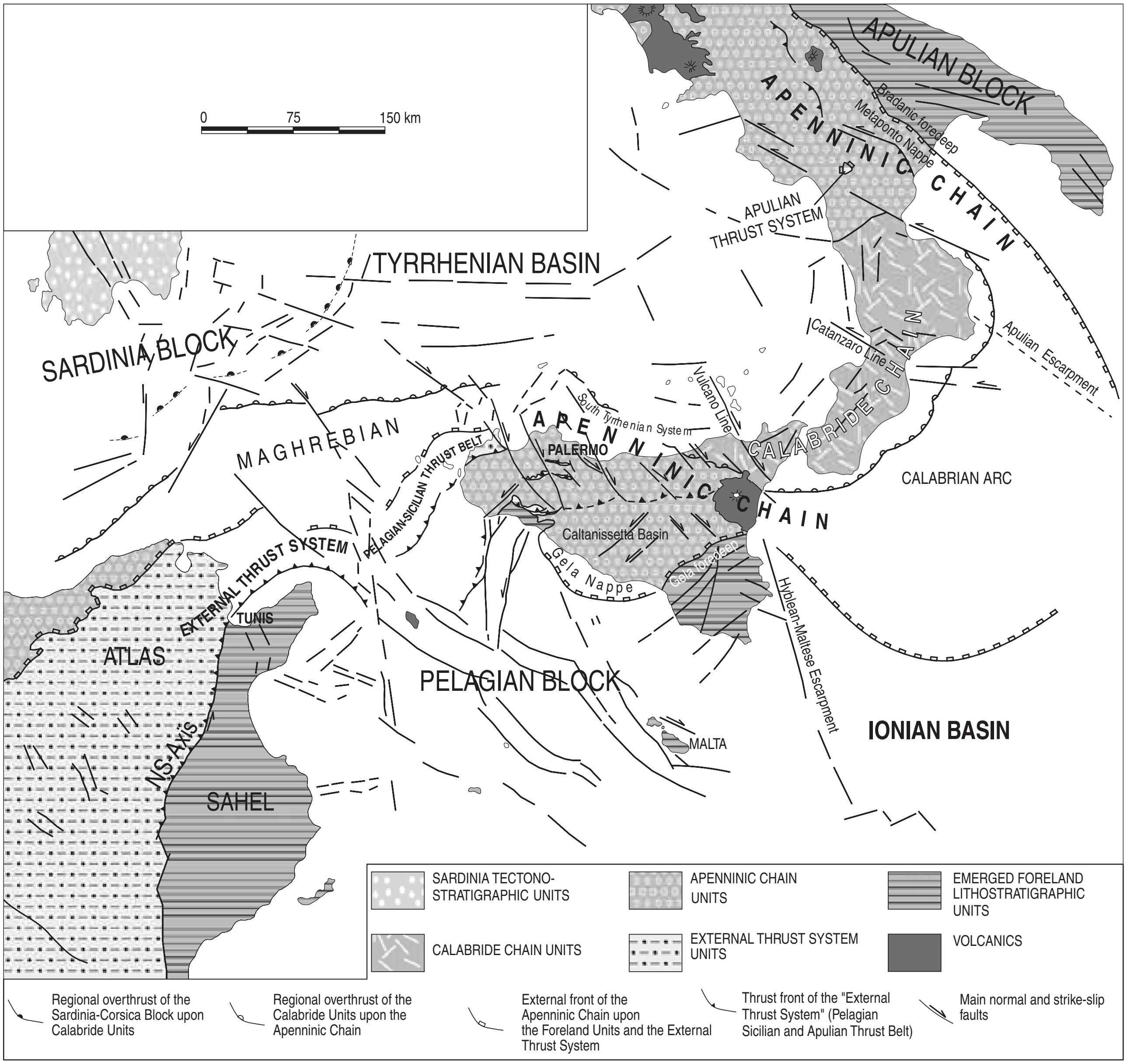


Figure 1. Regional distribution of the structural domains in the central Mediterranean (after Lentini et al., 1996). The Foreland domain consists of two blocks: the Apulian block (Adria continental crust) and the Pelagian block (Africa continental crust), separated by the oceanic crust of the Ionian basin. The lowermost structural level of the orogen is an external thrust system: Atlas in North Africa, the Pelagian-Sicilian thrust belt in Sicily, and the Apulian thrust system in the southern Apennines. These are overlain by the Apenninic-Maghrebian chain, a roof thrust system generated by post-Oligocene thin-skinned tectonics. This system, in turn, underthrusts an edifice composed of basement nappes derived by the Eocene–Oligocene delamination of the Europe plate's margin, the Calabride chain.

analogies between the two areas. For the Lucanian Apennines, the field data have been integrated with numerous subsurface data obtained from intensive petroleum research in the region; for Sicily, extensive field mapping throughout the island, numerous biostratigraphic analyses, and the collection of scattered subsurface data have been carried out. Relevant data about the distribution of various crustal types in this area of the central Mediterranean are derived from seismogeological profiles from the CROP-Mare project (Finetti et al., 2005a,b). Finally, a paleogeographical-paleotectonic model is proposed, and there is a final discussion of the current tectonics and an evaluation of the volcanological aspects.

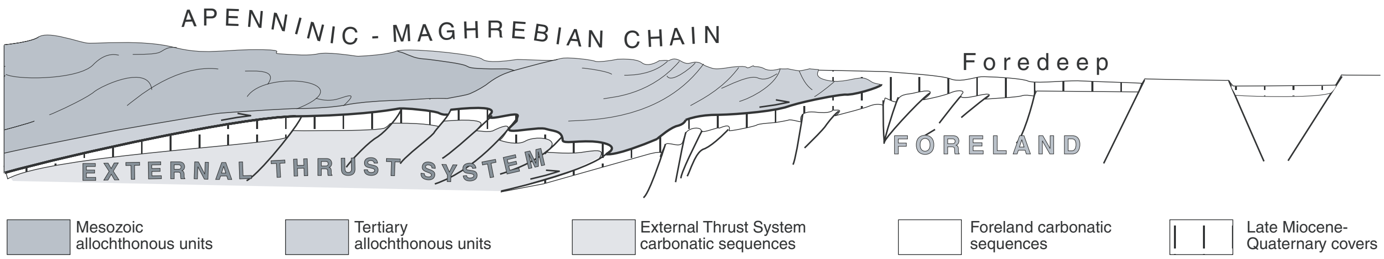


Figure 2. Structural domains of the Apenninic-Maghrebian orogen and their geometry along a southwest-northeast-oriented schematic cross-section of the southern Apennines. The orogenic belt shows a regional duplex geometry. The footwall is represented by the external thrust system (the Apulian thrust system in the southern Apennines). The Apenninic-Maghrebian chain consists of an allochthonous roof thrust system in which the Mesozoic and the Tertiary sequences are mostly decoupled.

THE REGIONAL TECTONOSTRATIGRAPHIC SETTING OF THE SOUTHERN APENNINES AND SICILY

In this section we present a synthetic description of the sequences that characterize the previously mentioned structural domains. Starting with the foreland domain, we describe the tectonic units of the Apenninic-Maghrebian chain, which are exposed particularly in the Lucanian sector of the southern Apennines and Sicily. A short discussion about the units of the Calabrian arc, the Corsica-Sardinia block, and the southern Tyrrhenian basin follows. We have clarified here the times and modalities of thrust propagation, the relationships between the "roof thrust system" of the Apenninic-Maghrebian chain and the deep-seated thrust belt of the external thrust system, and the repeated detachments of the Tertiary flysch-type sequences based mostly on the results of our recent field studies in the region (Lentini et al., 2002).

THE FORELAND DOMAIN

The foreland is represented by the undeformed portions of the Apulian block and of the Pelagian block, respectively belonging to the Adria plate and the Africa plate, and by the intervening Ionian basin (Fig. 1).

The Apulian Block

The Apulian block is characterized by a seismically well-defined continental crust containing a very thick meso-Cenozoic carbonate sequence and by a thin Pleistocene cover. The block extends northward along the Adriatic off-shore and represents the undeformed sector of the Adria plate. The thickness of this crustal block is ~32 km, which includes 8000 m of sedimentary covers, 15 km of upper crust, and 9 km of lower crust (Finetti et al., 2005a).

The Apulia Platform and the Bradanic Foredeep. The lowermost interval of the succession is composed of a 1000-m-thick Permo–Triassic sequence displaying alluvial and deltaic facies ("Verrucano facies") and recognized in the Puglia 1 well (from –6100 to –7070 m). This overlies a Precambrian crystalline basement detected with the help of geophysical data (AGIP Mineraria, 1968; Colombi et al., 1973; Cassinis et al., 1979; Morelli et al., 1979; Calcagnile and Panza, 1981). The Late Triassic anhydrite-dolomitic succession (Anidriti di Burano), resting unconformably on the "Verrucano facies" in outcrop and subsurface, is the product of sedimentation in a carbonate-evaporitic platform environment under a syn–rift tectonic regime. The succession is followed in stratigraphic continuity by 3000 m–thick, Jurassic–Cretaceous carbonate platform deposits.

The Paleogene deposits display the typical features of coastal marine and scarp environments, with transgressive clastic carbonate facies along the Adriatic margin and toward the Bradanic foredeep, and show distinct paleogeographic modifications corresponding to the emergence of the Mesozoic platform. The thickness of these successions varies from 350 m to ~100 m. The Neogene to Pleistocene cover is characterized by Serravallian-Tortonian organogenic and clastic carbonate facies, bauxitic clays, and marls and sands with thin diatomitic levels, of pre-evaporitic Messinian age. The Plio-Pleistocene sequences consist of clastic, glauconite-bearing carbonates typical of a neritic environment.

The Bradanic foredeep (or Bradano trough) represents the youngest foredeep basin of the southern Apennines and is characterized by a tectonosedimentary history that, during the Pleistocene, was influenced by local and regional structural elements related to the evolution of the Apulian foreland. This foredeep flexured during successive deformative phases and progressively migrated eastward (D'Argenio et al., 1973; Ciaranfi et al., 1979; Casnedi, 1988; Pieri et al., 1996). This behavior is demonstrated by the on-lap geometries of the infilling deposits on top of the carbonate substratum, well recognizable in seismic lines.

The physiography of the Bradanic foredeep has strongly influenced the depositional sequences related to both lithofacies and thicknesses. It is defined by an eastern external margin with carbonate sedimentation, a depocentral area occupied by the "subapenninic clays unit," and an internal western margin characterized by the frontal wedge of the Apenninic-Maghrebian chain, the so-called Metaponto nappe (Ogniben, 1969), intercalated within the sand to clay-rich Pliocene–Quaternary regressive sequences.

Toward the foreland, tilted reflectors in seismic profiles that are truncated by the overlying clastic wedge testify to active flexure-hinge retreat between 2.13 and 1.83 Ma. According to Cinque et al. (1993) and Patacca and Scandone (2004), around the early–middle Pleistocene boundary, flexuring of the lower plate ceased and the entire region began to uplift. In this article, this uplift process has been interpreted as evidence of the present-day collision between the Apulian continental crust and the continental crust detected in seismic lines shot in the Perityrrhenian area (discussed later).

The Pelagian Block

In Sicily the foreland domain (Ben Avraham et al., 1990; Lentini et al., 1994) is represented by the undeformed area of the Pelagian block, which extends from Tunisia to Sicily (Finetti, 1982; Burollet et al., 1987; Reuther, 1989; Argnani, 1990) and is characterized by a 25- to 35-km-thick continental crust (Cassinis, 1983; Scarascia et al., 2000). This crust underlies a 6- to 7-km-thick Mesozoic–Cenozoic shallow-water to basin carbonatic sedimentary succession, with repeated intercalations of volcanics. The Pelagian block represents an east-west segment of the Africa continental margin (Dewey et al., 1989) flexured to the north, beneath the orogenic belt.

The undeformed sequences of the Pelagian block crop out in the Sahel region of Tunisia and extend off-shore into the Sicily Channel, emerging in Lampedusa and the Malta islands, in the Sciacca area of western Sicily, and in the Hyblean plateau in southeastern Sicily (Fig. 1). Paleomagnetic data indicate that the geomagnetic pole positions are consistent with that of the Africa plate (Grasso et al., 1983).

On-shore, the folded Atlas to the west of the Pelagian block is separated by a tectonic discontinuity known as the north-south axis, representing a 5- to 8-km-wide deformed belt, extending from the Tunis Gulf in the north to Gabes in the south. The north-south axis has been interpreted as a left lateral transcurrent zone separating the folded areas of the Atlas Mountains from the undeformed areas of the Sahel (Boccaletti et al., 1989). It represents the western boundary of the undeformed Pelagian block.

A similar north-south-trending fault zone, the Hyblean-Maltese escarpment, bounds the Pelagian block to the east from the Ionian basin, a portion of foreland domain characterized by oceanic crust. This prevalently normal fault system partially affected the original margin of the Hyblean continental crust and was active during the Pliocene and the Quaternary (Scandone et al., 1981; Fabbri et al., 1982; Casero et al., 1984). According to Carbone et al. (1982a) and Grasso and Lentini (1982), in recent times the Hyblean-Maltese escarpment has been responsible for the progressive collapse of the eastern margin of the Pelagian block facing the Ionian basin. This also involved the eastern slope of Mount Etna volcano and plays an important role in the seismotectonic evolution of the area (Carbone et al., 1982b; Monaco et al., 2005).

The central portion of the Pelagian block is represented by the Sicily Channel. It occupies a large region of the Pelagian Sea and is characterized by a shallow-water epicontinental sea with an irregular bathymetry. This area is affected by intense rifting, which has led to the formation of three northwest-southeast-oriented deep troughs since the latest Miocene: the Pantelleria basin, the Linosa basin, and the Malta basin, with maximum depths of 1317, 1529, and 1731 m, respectively. These basins cut deeply into the Pelagian platform, generally less than 400 m. These grabens are separated from each other by normal, subparallel faults and filled with 1000- to 2000-m-thick Pliocene–Quaternary turbiditic and hemipelagic sediments (Maldonato and Stanley, 1977; Winnock, 1981). Rift-related alkalic volcanism is typical of this intraplate rifting. In correspondence with the axis of these tectonic depressions, comprising the so-called Sicilian Channel rift zone, crustal thinning is evident, with the Moho lying at less than 20 km depth (Colombi et al., 1973; Finetti and Morelli, 1973; Finetti, 1984; Buness et al., 1991). Here the plate is characterized by P-wave velocities that increase from 6.0 to 6.4 km/s in the upper crust to 6.5–7.2 km/s in the lower crust and by positive Bouguer gravimetric anomalies (from +40 to +90 mgal) (Morelli et al., 1975; Scarascia et al., 1994, 2000) and relatively elevated heatflow (less than 100mW/m) (Della Vedova et al., 1988).

The Hyblean Plateau and the Gela Foredeep. The northern part of the Pelagian block is flexured below the tectonic units of the orogenic domain. Flexural tectonics has led to a range of responses in the various segments of the foreland (Cogan et al., 1989). The Hyblean plateau represents an uplifted element separated from the flexured areas on its northwestern margin by a system of northeast-southwest-oriented normal faults, with considerable vertical downthrow. These faults delimit the Gela foredeep, which is fully occupied by the allochthonous units of the front of the chain, the Gela nappe (Bianchi et al., 1987; Grasso et al., 1990). Roughly north-south-oriented structures constitute the western margin of the plateau, separating it from a depressed sector of the foreland underplating allochthonous units. To the west of this lineament, the Miocene Hyblean successions have subsided to a depth of ~3000 m, which is ~4000 m lower than their counterparts outcropping on the plateau (Cogan et al., 1989). This major collapse of the Hyblean successions is accompanied by a significant southwestward areal extension of the Gela foredeep within which a distinct advance of the allochthonous units has occurred, forming a vast and largely submerged arcuate front (Argnani, 1989; Lentini et al., 1994; Finetti et al., 1996; Torelli et al., 1998). On a more general level, the major flexure of the foreland is reflected in the orogenic areas to the north, with the presence of a wide axial depression within the chain units. This depression is known in the literature as the "Caltanissetta basin" (Fig. 1), in which thick deposits of Messinian evaporites occur, deposited in the frontal regions of thrusts prograding toward external areas.

The northward extent of the foreland below the main thrust wedge in Sicily is well constrained, based largely on geophysical data and indirect geological reconstructions. Strongly deformed carbonate bodies connected to the successions of the Hyblean plateau have been detected below the allochthon of the orogenic belt as far as the northern slope of Mount Etna (Cristofolini et al., 1979; Lentini, 1982; Bianchi et al., 1987; Ben-Avraham and Grasso, 1991).

The autochthonous sedimentary cover of the Hyblean plateau has been detected down to a depth of ~6 km, where Middle Triassic layers have been found, while no information about the Permo-Triassic interval has been identified in the seismic lines (Bianchi et al., 1987). The age of the underlying crystalline basement is poorly known, but on mainland Tunisia, Precambrian granites and metamorphic rocks have been drilled (Burollet, 1991). The sedimentary succession is coupled with its crystalline basement and consists of thick Triassic–Liassic platform carbonates with intercalations of mafic volcanics overlain by Jurassic–Eocene pelagic carbonates and Tertiary open-shelf clastic deposits (Patacca et al., 1979; Bianchi et al., 1987; Lentini et al., 1987b).

Exposed sedimentary rocks on the Hyblean plateau are mostly of Tertiary age (Grasso and Lentini, 1982). Early Pleistocene shallow-water bioclastic carbonates and sands with beach conglomerates are located along the margins of the plateau. The Tertiary paleogeographic picture, unchanged until Messinian times, shows a totally new arrangement after the Pliocene, when the northeastern sector of the Hyblean plateau ceased to play the role of a structural high and progressively collapsed in connection with the development of the Hyblean-Maltese escarpment.

The Hyblean plateau has been the site of intermittent volcanic activity from the Triassic up to the early Pleistocene. While the products of the Mesozoic phases are buried, Late Cretaceous submarine volcanics topped by rudist-bearing carbonates are known in the eastern Hyblean area and off-shore, extending to the east of Malta. Hydromagmatic volcanic activity in a shallow marine environment resumed in the late Miocene. The composition was mafic alkaline.

Early Pliocene mafic alkaline volcanism continued in the northwestern part of the plateau. The late Pliocene activity was marked by a drastic compositional change from mafic alkaline to tholeiitic and by the eruption of large volumes of lava. This activity occurred when to the northwest the Hyblean foreland collapsed and a system of normal faults developed, originating the foredeep (Behncke, 2001). The thick volcanic layers drilled in the foredeep (Longaretti et al., 1991) are well correlated with the volcanics of the northern margin of the Hyblean foreland, but include a younger unit in the subsurface of the Catania Plain, which indicates a shift of volcanic activity toward the Etna area.

The Sciacca Platform. Seismic profiles and well data indicate a lateral facies transition from the Hyblean domain toward the Sciacca domain in southwestern Sicily (Catalano, 1987; Antonelli et al., 1988). The interpretation of the CROP M23A line shows the continuity between the Sciacca area and the Hyblean plateau (Finetti and Del Ben, 2005).

The Ionian Basin

The two continental blocks belonging to the foreland domains are separated by the Ionian basin (Fig. 1). This basin is delimited by the Hyblean-Maltese escarpment and the Apulian escarpment to the northeast. The latter displays a northwest-southeast orientation and runs from the Tyrrhenian coast of Cilento to off-shore of Crotone (eastern Calabria).

Various CROP data clearly confirm that the Ionian Sea is floored by an old oceanic crust (Finetti, 1982; Finetti et al., 2005b, and references therein). Analysis of the Paleo-Ionian covers, at the present time detached and tectonically transported into Sicily and the southern Apennines, supports the view that the Ionian Sea opened in Permo-Triassic times. The same data indicate that these basinal sequences (the Ionides) floored branches of the original Paleo-Ionian Sea, defining the paleogeography of the subducted portion of the oceanic crust. The CROP data provide important information, showing a clear image of the Ionian slab beneath the crustal fragments toward the Tyrrhenian Sea (Finetti, 2004, 2005). The hypothesis of an active subduction zone is also supported by volcanic activity of the Tyrrhenian Sea and geophysical data (discussed later). The frontal part of the Calabrian arc, drowned by the Ionian Sea, developed an accretionary wedge onto the subducting Ionian lithosphere.

THE OROGENIC DOMAINS

The External Thrust System

The innermost margins of the carbonate blocks of the foreland domain have been deforming since late Miocene times, giving rise to external thrust systems: the Apulian thrust system in southern Italy and the Pelagian-Sicilian thrust belt in Sicily and adjacent seas, mainly tectonically overlain by the roof thrust system of the Apenninic-Maghrebian chain (Fig. 2).

The Apulian Thrust System. In the Southern Apennines, the Apulian Thrust System is mainly buried, but well known from hydrocarbon exploration. Below the allochthonous wedge the Apenninic-Maghrebian chain, numerous boreholes have encountered horizons of variable age, ranging from the late Miocene to early Pliocene, which stratigraphically rest upon Jurassic-Cretaceous limestones deposited in a neritic environment. These sequences represent a portion of the Apulian foredeep overridden by the allochthonous wedge of the chain, which was involved during Pliocene times in the deformation and development of the Apulian thrust system.

Alternative interpretations of the structural setting are presented by Casero et al. (1991), Menardi Noguera and Rea (2000), and Patacca and Scandone (2004). In the former two papers, the buried Apulian platform is illustrated as affected by folds and reverse faults mostly of relatively moderate horizontal offsets. In the last paper, the deformed Apulian platform is interpreted as a duplex system characterized by thrust sheets with a remarkable shortening. Lentini et al. (2002) distinguish in the Apulian thrust system two tectonic units: an inner unit (the Mount Alpi unit), which originated from thin-skinned tectonics in the early Pliocene, and an outer unit (the Rotondella unit), which has resulted from thick-skinned tectonics since the middle–late Pliocene. Both tectonically underlie the roof thrust system of the Apenninic-Maghrebian chain.

The Pelagian-Sicilian Thrust Belt. This name is used to indicate the Sicilian external thrust system originating from the detachment of the sedimentary covers of the inner margin of the Pelagian block. It is mainly buried below the unrooted nappes of the Apenninic-Maghrebian chain (Fig. 2). The Pelagian-Sicilian thrust belt is exposed in western Sicily, while in the eastern sector of the island it has been detected only in seismic lines. In western Sicily, it consists of Triassic–Liassic shallow-water carbonates, Middle Jurassic to early Oligocene pelagic carbonates, and late Oligocene to early Tortonian continental shelf to slope syntectonic terrigenous and biocalcarenitic deposits.

The geoseismic and geological cross-sections show that the architecture of the westernmost part of Sicily is that of a thick wedge of meso-Cenozoic carbonate platforms beneath a tectonic stack of nappes. The carbonate thrust system consists of northward-dipping ramplike imbricates arranged in large antiforms with northwest-verging back-thrusts. As in the southern Apennines, the outermost units of this thrust belt are affected by modest shortening, observed in the seismic line of western Sicily (Finetti et al., 2005a). The meso-Cenozoic carbonates are followed upward by Serravallian–early Tortonian marls. The age of these siliciclastics indicates that these areas were affected by the thrusting relatively late and allows us to locate them in an outer paleogeographic context.

In eastern Sicily, the Pelagian-Sicilian thrust belt is not exposed, but it has been detected with the help of seismic lines interpreted in the context of the time-space evolution of the whole orogen (Lentini et al., 1994). In the seismic lines, a signal interpreted as the top of carbonate sequences is clearly identifiable from the deep-seated thrust system and extends as far as the Tyrrhenian shoreline. Below the northern chain of Sicily and in the southern Apennines, the seismic lines show a general culmination. This has influenced the geodynamic and the geomorphological evolution of the outcropping units of the roof thrust system.

The Apenninic-Maghrebian Chain

The Apenninic-Maghrebian chain is widely exposed in the Southern Apennines and in Sicily (Fig. 1) and consists of an allochthonous thrust system including Mesozoic sedimentary sequences detached from both oceanic and continental crusts and of Cenozoic flysch-type cover (Fig. 2). A general structural feature of this allochthonous chain is the decoupling between the Mesozoic sequences and the Tertiary covers that form, particularly in the Apennines, an imbricated thrust system directly overlying the Pliocene top levels of the Apulian thrust system. This regional feature, complex in detail, is nevertheless well known in general outline based on field geological mapping integrated with seismic lines and well logs (Lentini et al., 2002).

The Sicilian Apenninic-Maghrebian chain roof thrust system (Fig. 2) widely overthrust the Pelagian-Sicilian thrust belt and in some cases tectonically overlies the margin of the foreland with the Gela nappe. The Apenninic-Maghrebian chain originated in the late Oligocene, first at the expense of the Alpine Tethys basinal sequences, which floored the oceanic crust (the Liguride and Sicilide Units), and successively since the middle Miocene through tectonic denudation of continental crust sectors due to the orogenic transport of the allochthonous carbonatic covers (the Panormide-Apenninic platforms) onto the Ionian basinal successions (the Ionides). These latter are the deepest meso-Cenozoic tectonic units of the Apenninic-Maghrebian chain and are interpreted as the original deposits of branches of the Paleo-Ionian basin (Lentini et al., 1994, 2000, 2002; Finetti et al., 1996, 1997).

The Ionides are mainly constituted by Mesozoic–Eocene sequences grading upward into Oligocene–Middle Miocene terrigenous successions (Ogniben, 1960; Lentini et al., 1987a). The Permian–Triassic sequences, outcropping in western Sicily, can be ascribed to the Ionides. These confirm the Permian age of the opening of the Ionian basin. The Ionides were involved from middle Miocene to Pliocene times in orogenic transport onto the Apulian thrust system in the southern Apennines and onto the Pelagian-Sicilian thrust belt in Sicily. In the southern Apennines, the Ionides are represented by the so-called Lagonegro units, widely exposed in tectonic windows below the Apenninic platform units along the northwest-southeast culmination of the chain. In Sicily, they are widely exposed in the Sicani Mountains, in the mountains around Palermo, and in the Madonie Mountains (Imerese units), whereas in eastern Sicily they are mainly buried except in the Monte Judica area.

The Ionian Terrigenous Covers. The terrigenous deposits of the basinal sequences belonging to the Ionides are represented by Tertiary foreland or foredeep deposits whose relationships with the substratum are occasionally preserved, although large detachments occurred with further forward transport, which generated repeated slices with an apparent increase to the original thickness. The Oligo-Miocene deposits of the "Paleo-Ionian basin" are mostly constituted by the Numidian flysch and by external flysch or glauconite-bearing sequences grading up into middle–late Miocene siliciclastics. The Numidian flysch is characterized by Aquitanian-Burdigalian yellowish quartzarenites. The paleogeographical location of the Numidian flysch has been the subject of intense controversy in the geological literature concerning the provenance of the quartzose detritus that constitutes the formation. This is especially so with respect to the original source area of the sediments, whether these were derived from orogenic zones or from cratonic areas in Africa (Ogniben, 1960, 1963; Broquet, 1970; Caire, 1970; Dueé, 1970; Wezel, 1974; Grasso et al., 1978; Giunta, 1985; Lentini and Tortorici, 1986; Bianchi et al., 1987).

In synthesis the Numidian flysch forms a more or less autochtonous lower structural horizon (Lentini et al., 2000; Finetti et al., 2005b), named the external Numidian flysch, which is now composed of imbricated slices. This flysch succession originally was the cover of the Ionides and of the Panormide carbonate platforms. The overlying allochthonous horizon, the so-called far-traveled Numidian flysch, can be interpreted as part of the original cover of the Alpine Tethydes.

In Sicily and the southern Apennines, the quartzarenitic sedimentation typical of the Numidian flysch ceased everywhere at the end of Burdigalian times. The Ionian flysch-type sequences include the whole of the middle–upper Miocene turbiditic sequences—the Irpinian units of Cocco et al. (1972), or "Flysch Esterni" after Carbone et al. (1991)—which outcrop in the frontal wedge of the Apenninic-Maghrebian chain and are tectonically superimposed onto the Pliocene horizons of the Bradanic foredeep. To these sequences were also ascribed the satellite deposits resting unconformably on top of the allochthonous covers of internal origin.

The Panormide-Apenninic Units. These tectonic units are characterized by thick carbonate platform sequences, prevalently of Mesozoic age, whose striking facies uniformity and outcrop continuity as well as their tectonic setting preclude an unequivocal geometrical original location in the environment of the chain and any unambiguous reconstruction of their original paleogeographic position.

In the southern Apennines, these units, derived from the deformation of the "Campano-Lucanian" carbonate platform, are partly dissected, and they sank during the early–middle Liassic and were transported tectonically during Burdigalian–Langhian times. D'Argenio et al. (1973) attribute to the various stratigraphic-structural units of the Apenninic platform an origin from a common paleogeographic domain. These units correspond to the Panormide complex of Ogniben (1969), which includes thick allochthonous successions in carbonate platform facies, with an age ranging from the Middle–Late Triassic to the Paleocene.

In Sicily, the Panormide sequences crop out in the northern sector of the Palermo Mountains and in the Madonie Mountains and have been detected eastward in some boreholes for hydrocarbon research (Bianchi et al., 1987). Geophysical data indicate a continuity eastward to the Calabrian arc. The Panormide sequence starts with Late Triassic marls and is overlain by reefal carbonates ranging in age from Norian to Middle Cretaceous. Upper Cretaceous–Eocene wackestones and red marls (Scaglia facies), Oligocene fine-grained marls, quartzarenites, and calcarenites follow upsection. This sequence is stratigraphically overlain by the Numidian flysch (late Oligocene–early Miocene). The Panormide units tectonically overlie the Ionides, and in particular override the Imerese sequences.

The Alpine Tethydes. The Alpine Tethydes are composed of sedimentary sequences that were deposited in the Alpine Tethys and originally were located between the European block and the Panormide-Apenninic platforms. They are represented by allochthonous far-traveled tectonic units resting on both the Panormide-Apenninic platforms and the Ionides. Because of their "tectonic mobility," they have reached the frontal wedges in the foredeeps (the Bradanic foredeep in the southern Apennines and the Gela foredeep in Sicily) (Fig. 1). In the southern Apennines, it is possible to separate the ophiolitic-rich and semimetamorphic units (the Ligurides), which represent the unique evidence of an Eo-Alpine orogenesis, from those cover sequences containing tuffitic sands derived from the erosion of an Oligocene volcanic arc (the Sicilides) related to a Balearic phase (discussed later).

The sedimentary succession of the Sicilide units (Ogniben, 1960) was originally deposited in the Alpine Tethys realm and is characterized by Upper Jurassic–Oligocene basinal shales and mudstones. These evolved into upper Oligocene–lower Miocene terrigenous turbiditic successions. In Sicily, the "Complesso Sicilide" (Ogniben, 1960) included, in its original definition, the basinal sequences that represent the uppermost structural layer, previously deformed and tectonically underlying the crystalline nappes of the "Complesso Calabride." This is why these successions were assigned to an inner paleodomain corresponding to the "Bacino Eugeosinclinalico" of the old geological literature, closely linked to the inner crystalline massif today identified as the original European margin. In the southern Apennines as well as in Sicily, varicolored shales known as "Argille scagliose" or "Argille varicolori," related to Sicilide units, are widely exposed. They are very similar to the "Argille scagliose" of the northern Apennines.

Lentini et al. (1996, 2000) emphasized that the architecture of the Sicilides on the island is that of a tectonic wedge progressively thinning until it disappears below the Calabride chain. The geometric relations probably are the result of a progressive accretionary process accompanied by a general detachment of the Tertiary terrigenous covers and by a breaching of the Mesozoic intervals. In Sicily, the Sicilides generally overthrust the Numidian flysch slices and are unconformably covered by discontinuous Serravallian–late Tortonian terrigenous sediments.

The Tertiary Covers. Analysis of the Tertiary covers of the Alpine Tethydes allows us to recognize the role of the terrigenous deposits and provides precious information about the paleogeography and the paleotectonic evolution of this inner basin. The innermost deposits, early Oligocene in age, form an accretionary wedge located on the Apenninic-Maghrebian chain in front of the leading edge of the Calabride units outcropping in northeastern Sicily. The analysis aids us in dating the tectonic events, in particular the overriding of the Calabride edifice onto the Apenninic-Maghrebian one, the rotation of the Corsica-Sardinia block, and the geodynamic evolution of these structural domains. The composition of the sandstones of the Troina-Tusa flysch, which are rich in tuffites, allowed Ogniben (1964) to recognize a volcanic arc as their source. In the southern Apennines, this flysch is well exposed along a northwest-southeast trend, at the present belonging to the frontal wedge of the Apenninic-Maghrebian chain.

The Calabride Chain. This chain is part of an orogenic belt that extends from the southern Apennines to North Africa via the Calabrian arc and Sicily (Fig. 1). The Calabrian arc, or the so-called Calabria-Peloritani arc (Amodio Morelli et al., 1976), is an arc-shaped belt interpreted as the effect of migration toward the southeast of an arc-trench system. It is represented by crustal fragments overriding the Apenninic-Maghrebian chain along the submerged margin of the Ionian Sea. The edifice is composed of unrooted nappes in which several tectonic units can be distinguished. They are formed by Triassic phyllites, evaporites, and dolomites and by Jurassic limestones, ophiolite-bearing sequences, and several tectonic units composed of pre-Alpine crystalline basement, sometimes with remains of the meso-Cenozoic sedimentary covers.

Different interpretative models have been debated in the recent literature, as follows:

1. The Calabride crystalline nappes originated from the European continental margin and during the Neogene overrode the Apenninic-Maghrebian units (Ogniben, 1969, 1973; Bouillin et al., 1986).
2. The crystalline nappes were derived from an Austroalpine belt belonging to the Africa continental margin. In Cretaceous–Paleogene times, they were piled up together with the ophiolite-bearing units, forming a Europe-verging fragment of an Eo-Alpine chain. Afterward, during the Neogene, this edifice was affected by regional Africa-verging tectonics and overrode the Apenninic-Maghrebian chain (Bonardi et al., 1993, and references therein).

Many authors (Bonardi et al., 1982, 1993; Dercourt et al., 1985) distinguish two sectors of the Calabrian arc because of differences of composition, structural position, or thermobaric characteristics of the alpine metamorphic overprint. Furthermore, in southern Calabria the ophiolite-bearing units are absent, while early Miocene flysch-type deposits (the Capo d'Orlando flysch) occur. In northeastern Sicily the Calabride chain, corresponding to the Kabilo-Calabride chain *sensu* Lentini et al. (1994), includes nappes of Hercynian basement with remains of the original meso-Cenozoic covers deformed during the Paleogene and sutured by late orogenic levels starting in the late Oligocene.

The Tertiary Terrigenous Covers of the Calabro-Peloritanian Arc. Terrigenous covers crop out in the northeastern sector of Sicily (the Peloritani Mountains) and in southern Calabria, ranging in age from the late Eocene to the Miocene. These are sometimes present at the top of the meso-Cenozoic sequences and thus seem to have preceded the tectonic phases that led to the emplacement of the various crystalline units. Elsewhere, they suture the thrust contacts and are thus considered to have developed after the construction of the Calabride edifice. The composition of these covers suggests provenance of the detritus from areas of the Corsica-Sardinia block (Cherchi and Montadert, 1982; Rehault et al., 1984; Carmignani et al., 1986; Lentini et al., 1995b). The Oligo-Miocene terrigenous formations outcropping at the top of the Calabride units also extend onto the more internal Apenninic-Maghrebian chain units. The oldest deposits have been partly involved in late movements along the thrust of the Calabride chain onto the Apenninic-Maghrebian chain. The Burdigalian horizons mark the definitive sealing between the two chains. The late Oligocene–Burdigalian Capo d'Orlando flysch can be interpreted as a thrust top basin deposit that developed after the main emplacement of the crystalline nappes, but was involved in further tectonic phases.

THE HINTERLAND

The Corsica-Sardinia Block

The Corsica-Sardinia block is a microcontinent located between two oceanic basins: the western Mediterranean (Balearic basin) and the Tyrrhenian basin. It is characterized by a 30 km–thick continental crust and represents a segment of the Alpine orogenic system displaced from its original location, adjacent to the French continental margin, by counterclockwise rotation during the Oligocene–Miocene opening of the sestern Mediterranean Sea (Balearic stage). That is inferred from old paleomagnetic data obtained from the numerous volcanic outcrops (Montigny et al., 1981). The Corsica-Sardinia block belongs to the Europe plate and is composed of a Variscan basement locally covered by Carboniferous–Permian continental deposits and by Triassic carbonate sediments. A main transgression marks the beginning of the Jurassic platform carbonate sedimentation and is followed by Cretaceous and Tertiary limestones, conglomerates, and turbidites (Carmignani et al., 2004). In total, it represents a typical European-Briançonnais-type succession.

In northeastern Corsica, west-verging nappes composed of ocean-derived successions crop out. They are considered the southern continuation of the western Alps and are characterized by Jurassic ophiolites and their Jurassic–Early Cretaceous sedimentary covers overlain by Cretaceous–Oligocene flysch-type sequences. The oceanic realm in which these sequences were deposited is known as the Liguride domain, and it is part of the Alpine Tethys (Elter et al., 1966; Marroni et al., 2001).

In central–western Sardinia and in its continental margin, the Oligocene–Miocene extensional tectonics produced north-south-trending rift basins. Late Miocene postrift marine sediments were deposited, and andesites and calc-alkaline ignimbrites were erupted from 30 to 13 Ma. These latter are interpreted as the products of a magmatic arc generated by coeval subduction of an oceanic lithosphere along a NNW-dipping Benioff zone (Savelli, 1988). Thus, Sardinia can be considered a migrating magmatic arc affected by rifting and developing passive continental margin that opened toward the western Mediterranean Sea as a back-arc basin (Balearic stage).

Several submarine volcanic centers with orogenic affinity have been described off-shore along the southwest Corsica margin. These indicate that during the Burdigalian the Sardinia arc volcanism extended northward west of the Corsica coast (Rossi et al., 1997; Serri et al., 2001). Later, from the middle Pliocene, a northwest-southeast-oriented graben (Campidano) developed and was accompanied by magmatic activity producing alkaline basalts and undersaturated volcanics. This magmatism indicates that Sardinia had turned from a compressional setting with a magmatic arc to an intraplate setting or passive margin (Savelli, 1988).

CROP-Mare seismic lines clearly show the eastern passive margin of the Corsica-Sardinia block, which originated from the opening of the Tyrrhenian Sea. This extensional tectonic activity produced north-south–striking east-dipping normal faults (Fig. 3). These systems cut the stacked crustal units previously generated by the compressive Balearic tectonic phase and then are severely delaminated by Tyrrhenian mantle drag (Finetti, 2004; Finetti et al., 2005a,b).

During Tortonian-Messinian times, platform limestones passing to lagoon sediments were deposited. This evolution reflects the Messinian "salinity crisis" of the whole Mediterranean area. The Messinian regression was followed by a new early Pliocene transgression with marine sediments. The sequence is closed by continental Plio-Quaternary deposits.

The Southern Tyrrhenian Sea and the Crustal Setting of the Studied Area

The Tyrrhenian Sea is a triangular-shaped deep basin with a maximum depth of more than 3600 m. It has developed since Neogene times by means of extensional processes affecting the Alpine-Apenninic-Maghrebian orogenic system. From north to south the geophysical characters significantly change, and the basin can split into two parts separated by a magnetic and tectonic lineament running along the 41° parallel (Sartori, 2001). In the present article, the southern sector is briefly described, because it influences the current tectonics of the Calabrian arc system. Figure 3 illustrates a simplified scheme of the crustal setting, along with the distribution and thicknesses of the Tyrrhenian Sea and of the surrounding structural domains. The foreland is characterized by two continental crustal domains separated by the Ionian oceanic crust. Their inner margins have been deformed since the late Miocene, giving rise to the external thrust system. Two collisional crustal fragments are stacked onto the deformed Afro-Adriatic crusts.

The southern sector of the Tyrrhenian Sea is characterized by two abyssal basins floored by oceanic crust of different ages (ca. 1.8 Ma and 4.5–2.6 Ma for the Marsili and Vavilov basins, respectively; see Serri et al., 2001). A thin crust overlying a soft mantle is typical of the back-arc volcanism of the central Tyrrhenian Sea (the Magnaghi, Vavilov, and Marsili seamounts), where tholeiitic rocks dominate.

The Quaternary thin oceanic crust of the Tyrrhenian Sea (Marsili basin) is seismically evident. An undulating reflector within the oceanic crust is typical of zones close to the continental margin (the initial crustal opening). It has been interpreted as gabbroid plutons and is distinct from the flat overlying basaltic floodings (Finetti et al., 2005a).

In the western part of the Tyrrhenian Sea, a delaminated passive margin of Sardinia has been recognized in the seismic lines of the CROP-Mare project (Finetti, 2004). Crustal thickness decreases from 30 km in Sardinia to less than 10 km in the central area of the Tyrrhenian basin. This sector is characterized by a strong delamination of the crustal units belonging to the European continental margin and is floored by Messinian evaporitic sediments that indicate the age of the onset of the Tyrrhenian opening.

The CROP seismic lines crossing the submerged areas located along the area off-shore of northern Sicily and to southwest of the southern Apennines detected a 22-km-thick continental crust. This crust, previously named the "Maghrebian crust" by Lentini et al. (2002), is clearly the original basement of the Panormide-Apenninic platforms. The seismic lines show the relationships between the meso-Cenozoic carbonate sequences and this continental crust, from which they are more or less completely detached and transported onto the Ionides.

In the crustal profiles of Figure 4, obtained with the help of the seismic interpretation, it is clear that the continental crusts of the Adria and Africa plates extend beneath the orogenic belt that characterizes the on-shore areas to the Tyrrhenian shoreline. The Afro-Adriatic continental crusts show a progressive thinning and laterally grade into an old Ionian slab, now completely subducted. The aforementioned continental crust, detected off-shore in the Tyrrhenian and interpreted as the original crustal basement of the Panormide-Apenninic platforms, is currently colliding with the Adria continental crust and Africa continental crust, respectively, in the southern Apennines and Sicily.

The geologic evidence of this collisional setting are the northwest-southeast-oriented transcurrent faults, sinistral in the southern Apennines and dextral in Sicily. This latter is a well-known south Tyrrhenian system (Finetti et al., 1996) that affects both off-shore and on-shore areas of Sicily (Fig. 1). Of the south Tyrrhenian faults, the most significant is that of the Vulcano line. This NNW-SSE-oriented fault represents a boundary between the collisional setting to the west and the still subducting Ionian slab to the east. It crosses the Eolian islands and separates the islands with volcanic activity to the east (Vulcano, Panarea, Stromboli) from the western islands, where active volcanic phenomena seem to have stopped at the present time.

From a morphotectonic point of view, the Tyrrhenian sector located between the abyssal plain and the coastline of Sicily, Calabria, and the southern Apennines corresponds to a paleo-forearc basin developed since the late Miocene above the back-stop of the chain (the collisional crust of Fig. 3) and the accretionary wedge (the Calabrian arc).

In the Perityrrhenian area, three basins can be distinguished: the Paola basin, the Gioia basin, and the Cefalù basin (Fabbri et al., 1981). In some seismic lines it is possible to recognize the morphostructural elements that in their entity consti-

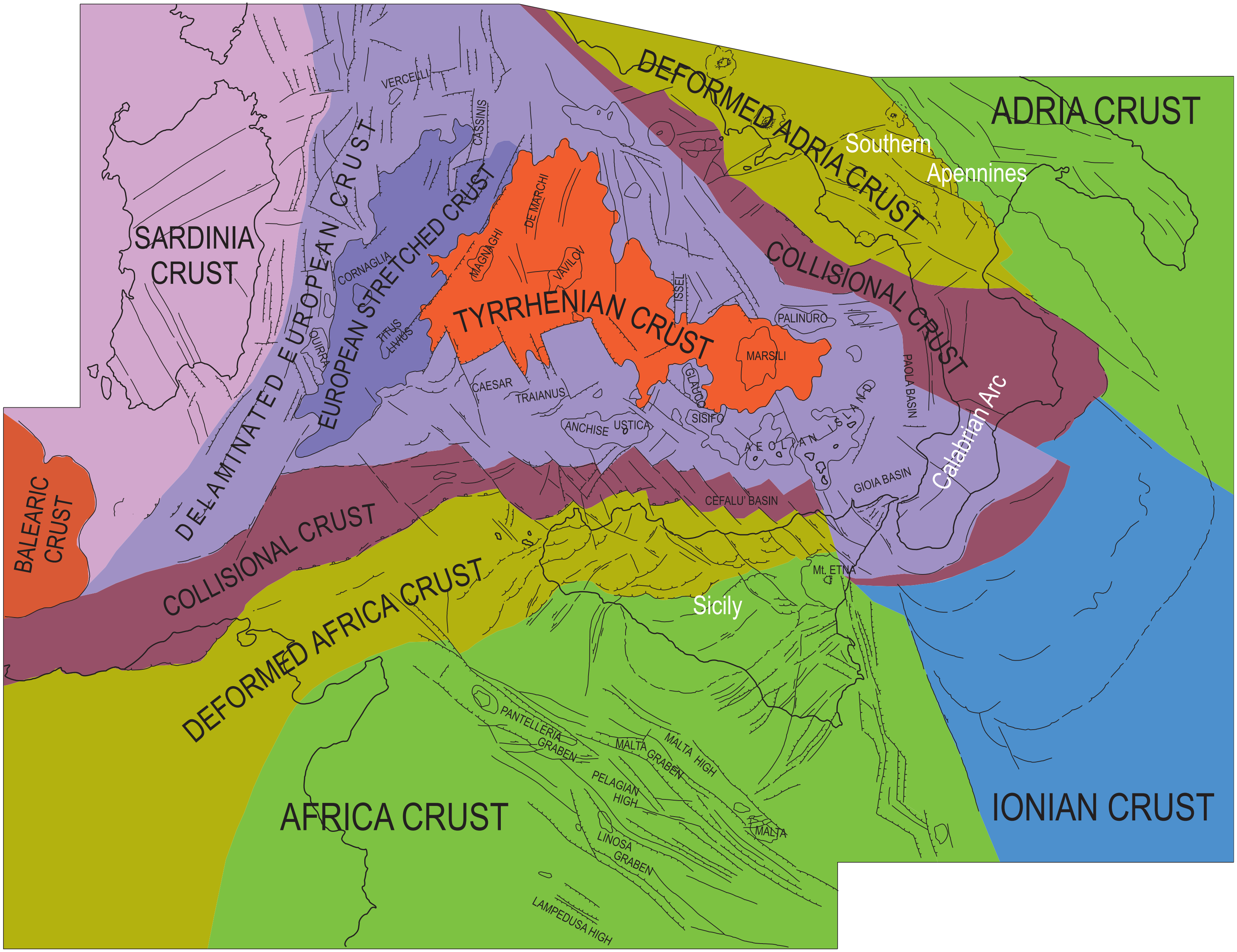


Figure 3. Sketch map of crustal domains in the central Mediterranean. The foreland domains are characterized by two continental crusts (Adria and Africa) separated by the old crust of the Ionian Sea. At the present time, the subduction of the Ionian crust is active only beneath the southern Calabrian arc. Remains of parts of the Paleo-Ionian slab are seismically recognizable between the deformed margins of the continental blocks and a collisional crust, the Panormide-Apenninic continental crust. The Tyrrhenian Sea is composed mostly of an oceanic crust that corresponds to the abyssal plain, a delaminated European crust intruded by the magmatic bodies of the volcanic arc, and the collisional crust above which the forearc basin developed.

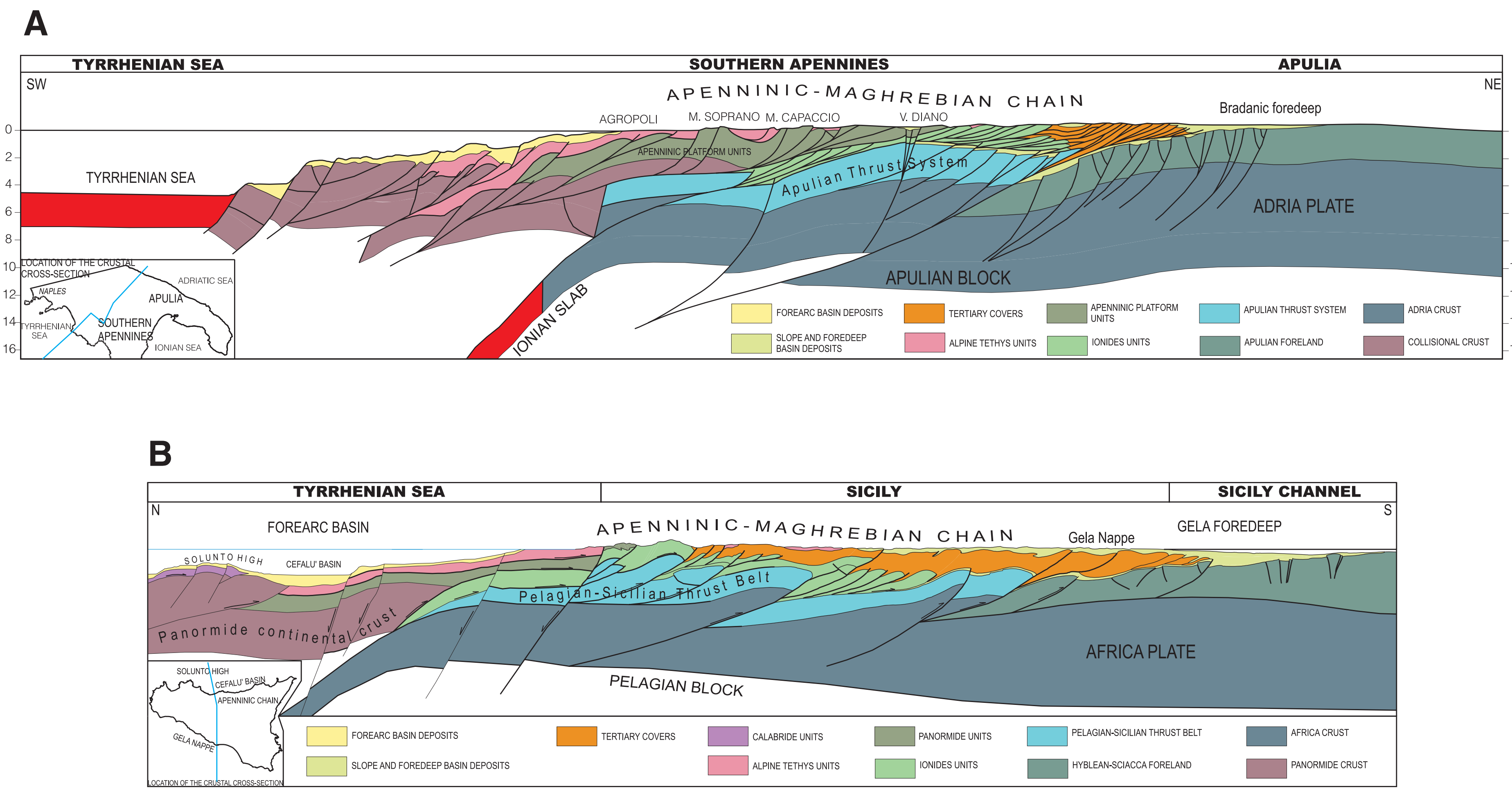


Figure 4. Crustal profiles across (A) the southern Apennines (modified from Finetti et al., 2005a) and (B) central Sicily (modified from Finetti et al., 2005b).

tute the paleo-forearc basin (Guarnieri, 2005). Of the three basinal areas that make up the southern Tyrrhenian complex, the Paola basin is the one where the paleo-forearc is most completely recognizable. The Paola basin is a slope basin parallel to the Tyrrhenian margin, in a NNW-SSE direction. To the west this basin is confined by submarine volcanic edifices that show a similar alignment, while to the east it is bordered by a system of normal faults that separate it from the emerged sector of Calabria. In contrast to the Paola basin, the Gioia basin has no intermediate ridge, but on the contrary constitutes an area whose characteristics are similar to those of the intra-arc sector confined to the northwest by the volcanic arc (Aeolian island). A considerable thickness of Plio-Pleistocene sediments is present (2500 m), and from a morphostructural viewpoint these characteristics are observed at least as far as the Catanzaro line to the south (Fabbri et al., 1982). To the west, the Cefalù basin is elongated parallel to the Solunto-Finale ridge and is confined to the south by a system of transtensive faults that were active from the late Pliocene up to late Pleistocene (Del Ben and Guarnieri, 2000). It is also linked to the northwest-southeast-oriented transcurrent system (Finetti et al., 1996) that corresponds to the limit between the sectors under compression to the south and those in extension to the north, and thus represents the southern margin of the forearc basin system.

The Aeolian volcanic arc is composed of seven islands and at least six volcanic seamounts aligned in a semicircular structure located west and northeast of the emerged arc. This archipelago with the Aegean one is the only active island arc segment in the Mediterranean. The formation of the Aeolian islands is thought to be the product of subduction-related calc-alkaline arc volcanism. In this sense, the Ionian oceanic crust is considered to be subducting northwestward beneath the Calabrian arc. The composition of the volcanic rocks varies greatly. The products consist of (high-K) calc-alkaline basaltic-andesitic to rhyolitic lavas and subordinate shoshonites and leucite-tephrites. A few arc tholeiites have been dredged from the submerged Aeolian slope (Beccaluva et al., 1985). According to the geochronological data available, the activity started in the Quaternary (ca. 1–1.3 Ma) at the Sisifo seamounts and at Filicudi. The magmatic evolution is typical of island arcs: after a first tholeiitic phase, calc-alkaline products predominate, while more potassic volcanics characterize the still active volcanoes of Stromboli and Vulcano (Beccaluva et al., 2004, and references therein).

THE ROLE OF THE TERTIARY TERRIGENOUS COVERS IN GEODYNAMIC EVOLUTION

After the Eo-Alpine orogenesis, the orogenic domains have developed since the early Oligocene and have progressively migrated from the innermost domains toward the outer ones. The foredeep migration has been well recorded by means of the diachronism of siliciclastics that become progressively younger away from the internal paleogeographic domains, in particular the rapid flexure-hinge retreat of the Ionia plate determined since the middle–late Miocene opening of the Tyrrhenian backarc basin and the contemporaneous forward migration of the thrust belt–foredeep system. The Miocene–Pliocene terrigenous covers thus well record the entire tectonic evolution of the area studied.

The following different areas of sedimentation can be distinguished: forearc basins, trench slope basins, satellite basins, foredeep basins, and foreland basins. With the progression of deformation there is generally an evolution from foreland deposits to foredeep deposits, to satellite and trench-slope deposits, and finally to forearc basin deposits in the hinterlands. Two main orogenetic stages are thus confirmed: a Balearic stage lasting from the Oligocene to the Burdigalian and a Tyrrhenian stage starting in the Langhian.

Forearc basin deposits are recognizable on-shore along the Tyrrhenian side of Sicily; Langhian marls and marly clays overlie in a top-lapping arrangement the south-dipping foresets of the Burdigalian-Langhian calcarenites or unconformably rest on a Langhian erosional surface. They are mostly pelagic fine-grained sediments and indicate a sudden change in the tectono-sedimentary regime, marking the demise of source areas that fed the clastic horizons of the calcarenites. Finally, an overall marine transgression flooded the previously emerged areas. There was a northward migration of clastic fans within newly created hinterland basins. This inversion gives valuable information about the age of the onset of the Tyrrhenian Basin and the progressive collapse of its southern margin. The areas feeding the middle Serravallian–early Messinian deposits successively collapsed after the Pliocene (Lentini et al., 1994). Their northwestward foreset geometries suggest that they were probably originally located on the modern Ionian side of northeastern Sicily.

Middle Serravallian–early Messinian deposits are preserved within down-faulted areas bordering the Peloritani ridge (in northeastern Sicily). They occur along the Tyrrhenian and Ionian slopes and are separated by a modern northeast-southwest-oriented horst structure upon which a few depositional remnants are scattered. The upper portion of the sequence consists of arenaceous-argillaceous alternations. It forms a topset geometry and dates to the upper Tortonian–lower Messinian. These deposits grade up into late Messinian evaporites.

The Troina-Tusa flysch can be ascribed to a trench-slope basin deposit and is interpreted as the original cover of the Alpine Tethydes. The tuffites indicate that a volcanic arc was their source. It is difficult to define the original paleogeographic location of this flysch. It seems to be related to a trench-slope deposit linked to the Burdigalian tectonic stage, the Balearic stage, and to the subduction of the Alpine Tethys oceanic crust beneath the European margin.

The "far-traveled" Numidian flysch is a largely allochthonous Numidian sequence recognized only in Sicily. It originally was deposited in the outermost part of the Alpine Tethys basin, more or less in continuity with the Sicilides. It was affected by deformational episodes during the post-Burdigalian compressive phases. Its lateral transition with the Troina-Tusa flysch is demonstrated by the composition of the arenites in the top levels. Thus the allochthonous Numidian flysch represents the late Oligocene to Burdigalian outermost sequence of the Sicilide accretionary wedge. A capping interval of Langhian marly clays plays the role of a syntectonic deposit.

In the southern Apennines, the outermost Oligocene–Miocene deposit of the Alpine Tethys basin is represented by the Albidona flysch, as indicated by the mixed siliciclastic and calciclastic sediment compositions. The source area is believed to be the Apenninic platform. This flysch can be interpreted as a foredeep deposit formed during the Oligo-Miocene Balearic stage and subsequently involved since the middle Miocene in the Apulia-verging thrust progradation during the Tyrrhenian stage.

The Neogene–Quaternary sequences are mostly represented by foredeep and thrust top basin deposits. As deformation proceeded, the areas of sedimentation were progressively involved in the orogenesis. During the Balearic stage, the Panormide-Apenninic platforms played the role of foreland until it was transformed into a foredeep with the more or less complete closure of the Alpine Tethys. After this stage, it overrode the Ionian domain from Langhian times to the beginning of the Tyrrhenian stage. In this geodynamic context, the external Numidian flysch, mainly in Sicily, occupied a wide area of the foreland that in the middle Miocene evolved into an extensive foredeep. In the southern Apennines, the Burdigalian-Langhian deposits present the first evidence of siliciclastic deposits fed by the tectonic wedge of the Tethydes. In Sicily, during the late Oligocene siliciclastics with megabreccias, interpreted as ramp deposits, originated from the carbonates of the Panormide platform. At this time, these units represented a foreland deposit. Laterally and upward the sequence grades into the Aquitanian-Burdigalian quartzarenitic banks of the Numidian flysch, as previously described. This sequence is terminated by a Langhian marly interval that marks the end of the exclusively quartzose sedimentation. These siliciclastics, deposited on wide foredeeps fed by the Alpine Tethydes frontal wedge, were subsequently covered tectonically by the Sicilides during Langhian–Serravallian times. In the frontal wedge of the Apenninic-Maghrebian chain in the southern Apennines, the middle–late Miocene external flysch represents the foredeep deposit (Irpinian basin) and has been successively incorporated into the thrusting, while coeval satellite deposits rest unconformably on the units of the chain.

In Sicily, the Numidian covers are coeval with glauconitic sequences. These represent outermost epicontinental deposits affected by tectogenesis only since Tortonian times. These deposits underthrust an allochthonous mélange composed of the Alpine Tethydes and the “far-traveled” Numidian flysch, in turn overlain unconformably by the late Tortonian siliciclastics. In contrast, on the outermost areas the sedimentation has been more or less continuous since the Langhian and testifies to the late involvement of these areas.

The carbonate sequences of the Pelagian-Sicilian thrust belt outcropping in western Sicily at the Monte Kumeta and Rocca Busambra ridges and in the Trapani Mountains are considered “external” sequences. These are overlain by early Miocene glauconitic biocalcarenites. These pass upward into marls, which are effectively Tortonian foredeep deposits.

The migration of the chain-foredeep system brought the progressive involvement of the aforementioned sectors of the foredeep with the formation, during the late Miocene–Pliocene, of accretionary wedges and satellite basins. In central Sicily (the Caltanissetta basin), it is possible to distinguish a wedge constituted by sandy-clayey and conglomeratic sequences with intercalations of a mélange derived from the Sicilide units and of olistostroms unconformably overlain by thrust top basin deposits, mainly constituted by late Tortonian siliciclastics. This is a transgressive sequence that rests on a substratum made of the allochthonous deposits of the Sicilide units and passes upward into Messinian evaporites and early Pliocene chalks. The entire sedimentary succession is strongly deformed with short-amplitude folds and represents the allochtonous wedge (Gela nappe) of Messinian–early Pliocene age overthrusting the present-day foreland margin.

The source areas of the late Miocene satellite basin deposits can be related to a crystalline basement recognized by seismic lines (Panormide continental crust) at the present time downfaulted in the Tyrrhenian off-shore (see the Solunto High in Fig. 4A). It represents the late Miocene–early Pliocene emerged chain, while the modern northern chain of Sicily played the role of the frontal wedge, as demonstrated by satellite basin deposits composed of early Pliocene chalks found in the Madonie Mountains at 1600 m above sea level.

In the Caltanissetta basin, two major Messinian evaporitic cycles have been recognized, separated by a regional angular unconformity. The lower evaporitic sequence is folded and truncated by an intra-Messinian unconformity and underlies deposits characterized by resediments originating from the lower units interbedded by selenitic gypsum. The lowest Pliocene chalks record the sudden flooding of the Mediterranean Sea by water from the Atlantic Ocean. These carbonates were deformed together with the evaporites during the early Pliocene tectonic phase. A second, middle Pliocene cycle is represented by marls and blue clays grading upward into sands and calcarenites and is unconformably underlain by a late Pliocene–early Pleistocene regressive sequence.

Recently some authors (Argnani et al., 1987; Bianchi et al., 1987; Lickorish et al., 1999), on the basis of data acquired from hydrocarbon research wells, from seismic lines off-shore of the southern coast of Sicily, and from on-shore geological data, have provided evidence that the allochthonous front of the Apenninic-Maghrebian chain (the “Gela nappe”) rests tectonically upon the Pliocene deposits. Furthermore, the early Pleistocene horizons, sometimes slightly deformed, lap upon the frontal thrusts (Di Geronimo et al., 1978). Thus, since the upper Pliocene the allochthonous front has tended to slow its advance, and it came to a complete halt in the lower Pleistocene. This can be connected with the modern collisional setting between the Africa plate and the Panormide crust recognized along the Tyrrhenian margin of the island. The Gela nappe winds southwestward in the direction of the Gela off-shore, from which it extends to the Adventure shelf (Argnani et al., 1987). The Gela foredeep breaks off in western Sicily, where the present foreland-chain boundary consists of a complicated Plio-Pleistocene trascurrent belt (Argnani et al., 1987).

The Pliocene–Pleistocene deposits in the southern Apennines as well as in Sicily significantly contribute to the understanding of relationships between tectonics and sedimentation in the active thrust belt–foredeep system, because the foredeep basins' thrust-related depositional sequences are well preserved. In particular, the Pliocene–Pleistocene thrust belt–foredeep system in the southern Apennines and in Sicily has been precisely analyzed by Patacca and Scandone (2004). In the southern Apennines, Messinian evaporitic horizons have been encountered only in the subsurface in wells within the Metaponto nappe, where they rest upon the carbonate substratum of the Bradanic foredeep and the Apulian thrust system. In this area, the Plio-Pleistocene covers were deposited in a chain-foredeep-foreland system. During the Pliocene, satellite deposits on top of the units of the Apenninic-Maghrebian chain participated, along with the entire allochthonous wedge, in the overthrusting on top of the Apulian thrust system. In this framework the covers, which rest unconformably upon the Apenninic-Maghrebian chain units that were transported along with the allochthonous substratum, assume a different structural role with respect to the coeval deposits emplaced directly upon the Apulian substratum, which today are encountered only in drillholes at depth.

The presence of early Pliocene horizons below the hangingwall of the Apenninic-Maghrebian chain in a relatively internal area suggests that much of the overthrusting of the roof-thrust system on top of the Apulian carbonate substratum has occurred since the middle Pliocene. It is only in the frontal areas, at the base of the Apenninic-Maghrebian chain, that units of the middle Pliocene to Quaternary have been involved, up to the deposits containing *Hyalinea baltica,* within which the front of the Metaponto nappe is located. These latest deposits extend only as far as the suture of the allochthonous front, which thus is buried, and they extend without any break in continuity to the relatively undisturbed Plio-Pleistocene foredeep deposits.

The deposits related to the three different sedimentary cycles cover progressively more internal areas of the nappe edifice, showing modest basal diachronies. The tectonic context within which the deposition of the Plio-Pleistocene series took place was thus characterized by an intense mobility of the substratum, as recorded by the presence within the successions of several stratigraphic discontinuities that extend over the entire southern Apennines and are classically associated with transgression and regression events on a regional scale.

PALEOGEOGRAPHIC AND PALEOTECTONIC EVOLUTION

The Ionian basin, opening since Permian-Triassic times within the Adria plate, separates the Apulian block from the "Apenninic" block. Northward along the Apennines, the Ionides, represented by the Lagonegro basinal sequences, progressively disappear. This indicates that the Ionian crust was narrowing and that both continental blocks, the Apulian block and the "Apenninic" block were joined in an unique continental plate: the Adria plate. Similarly, there is no continuity of the Ionides toward western Sicily, and this may indicate the progressive closure of the oceanic crust and the direct connection of the two continental crusts (i.e., both the Africa and the Panormide crusts). That means that to the west the Panormide crust is part of the Africa plate.

Figure 5 depicts a highly schematic paleogeographic and paleotectonic reconstruction of the area from the European to the Apulian margins with the interposition of the continental crust recognized in the CROP-Mare lines M6B and M29b. An Alpine Tethys basin was located between the Europe and Adria-Africa plates (Fig. 5A).

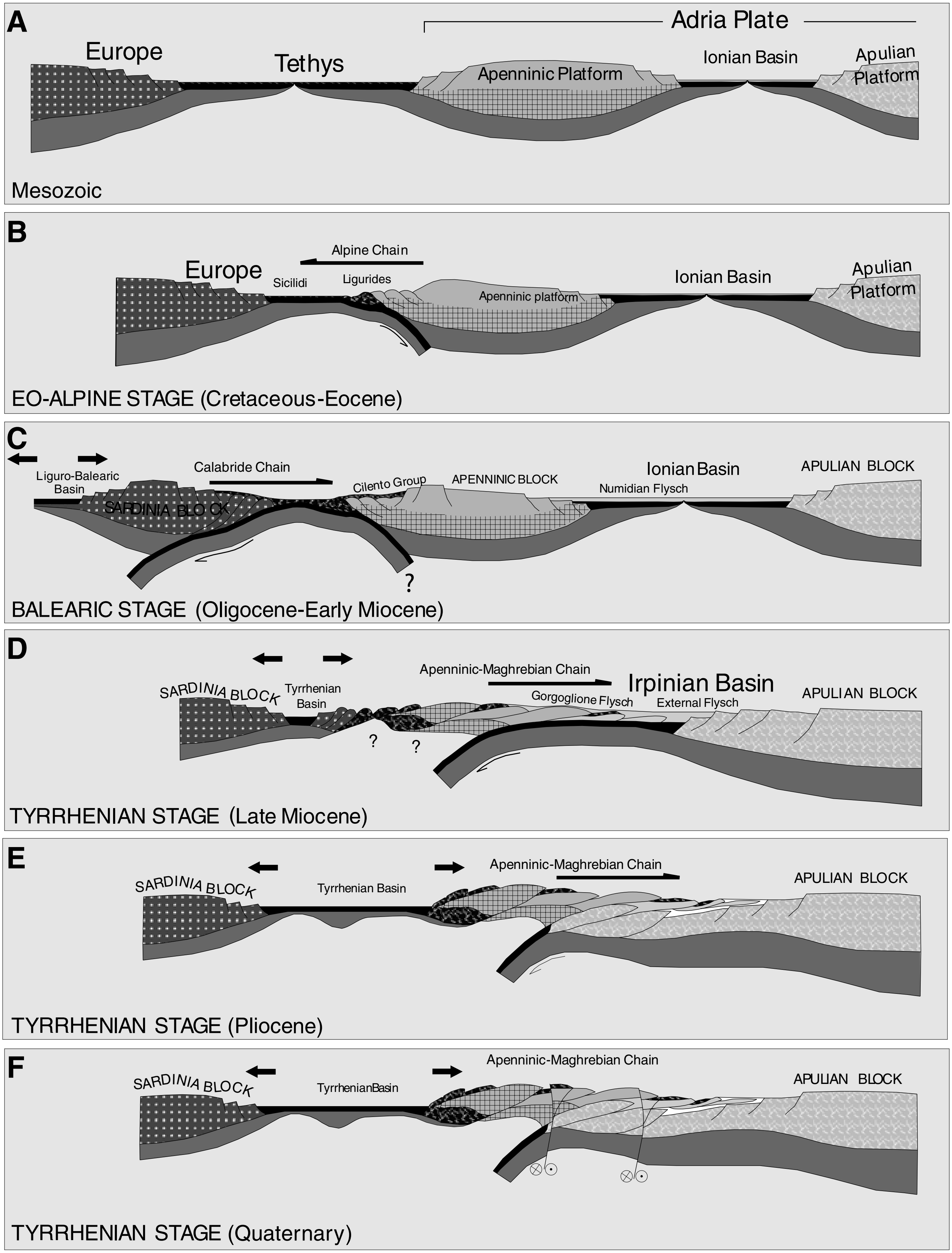
The geodynamic evolution of the convergent system that led to the structuration of the southern Apennines and Sicily can be summarized as follows.

The Eo-Alpine Stage

Scarse evidence of an Eo-Alpine stage can be observed in the area studied. However, the evidence is enough to recognize the Eo-Alpine stage developed during Late Cretaceous–Eocene times. The Africa-Ionia-Adria plate as a unique composite plate and the Eurasian plate converged during this stage (Fig. 5B).

On the Tyrrhenian side of northern Calabria, in the "Catena Costiera," a tectonic wedge composed mainly of Ligurides and ophiolites-bearing sequences formed verging toward Europe. This section has been interpreted by Amodio Morelli et al. (1976) as a fragment of an Eo-Alpine chain.

Figure 5. Paleogeographic reconstructions along a west-east-oriented transect from Sardinia to the southern Apennines. (A) During Mesozoic times, the Europe and Adria plates were separated by the Tethys Ocean. (B) During the Eo-Alpine stage, the Alpine orogen was built up, driven by the southward subduction of the Tethys Ocean below Adria during the Cretaceous–Eocene. (C) From the beginning of the Oligocene (Balearic stage), a northward subduction of a remnant Tethys Ocean occurred. (D) The first evidence of the beginning of the Tyrrhenian opening is found in the middle–late Miocene, but the oceanization has been recorded in some parts of the Vavilov basin from Pliocene times (E). The subduction hinge retreat of the Ionian litosphere caused the southeastward migration of the tectonic system and the development of a transcurrent system linked to collision of the crustal root of the chain against the crustal elements of the foreland (F).


A
Adria Plate
Europe
Tethys
Apenninic Platform
Ionian Basin
Apulian Platform
Mesozoic
B
Alpine Chain
Europe
Sicilidi
Ligurides
Apenninic platform
Ionian Basin
Apulian Platform
EO-ALPINE STAGE (Cretaceous-Eocene)
C
Liguro-Balearic Basin
Calabride Chain
SARDINIA BLOCK
Cilento Group
APENNINIC BLOCK
Ionian Basin
Numidian Flysch
APULIAN BLOCK
?
BALEARIC STAGE (Oligocene-Early Miocene)
D
SARDINIA BLOCK
Tyrrhenian Basin
Apenninic-Maghrebian Chain
Gorgoglione Flysch
Irpinian Basin
External Flysch
APULIAN BLOCK
?
?
TYRRHENIAN STAGE (Late Miocene)
E
SARDINIA BLOCK
Tyrrhenian Basin
Apenninic-Maghrebian Chain
APULIAN BLOCK
TYRRHENIAN STAGE (Pliocene)
F
SARDINIA BLOCK
TyrrhenianBasin
Apenninic-Maghrebian Chain
APULIAN BLOCK
TYRRHENIAN STAGE (Quaternary)

On the Calabria-Lucania boundary, Jurassic–Cretaceous ophiolites and low metamorphic rocks belonging to the Ligurides are sealed by the Oligo-Miocene Albidona flysch interpreted as foredeep deposits. At the present time, they are completely detached onto the Apenninic platform or directely overlying the Ionides tectonically, and they display an Apulian vergence that originated during the subsequent stages.

Analogous Alpine fragments are well known in northeastern Corsica, and relevant data from the CROP-Mare seismic lines reveal the presence in the Tyrrhenian Sea of north-verging ophiolite-bearing metamorphic thrust sheets. They are located off-shore of northwestern Sicily in an area characterized by large magnetic anomalies.

Outside the area studied, the subducted Alpine Tethys slab is clearly imaged in the ECORS (Étude Continentale et Océanique par Réflexion et Réfraction Sismique)-CROP seismic section crossing the western Alps, but has also been identified beneath the northwestern Adria plate as a lateral subduction of the Alpine Tethys (Finetti, 2004).

The Balearic Stage

This stage followed the previous Eo-Alpine phase and produced an orogenic belt with opposite vergence, toward the Adria-Africa block (Fig. 5C). In northeastern Corsica, the west-verging thrust systems that originated during the Eo-Alpine stage have been successively affected by the Adria-verging low-angle thrust faults of the Balearic stage. Prerift, syn-rift, and postrift sequences are seismically well defined (Finetti, 2004). This stage allowed a further consumption of the remnant of the Alpine Tethys oceanic crust and collision of the Europe plate with the Panormide-Apenninic crust. The consumption of the Tethys crust was contemporaneous with the emplacement of extensive frontal nappes, the opening of the Balearic back-arc basin, and the counterclockwise rotation of the Corsica-Sardinia block, which ended at the Burdigalian-Langhian boundary.

The flysch-type successions of late Oligocene to early Miocene age, characterized by tuffitic sandstones and most frequently occurring in the Troina-Tusa flysch and in some coeval siliciclastics outcropping along the Apennines (the Ranzano flysch and so on), testify to the presence of a volcanic arc that belonged to the Alpine Tethys subduction complex. Other evidences of the Balearic stage are the rifting of the western Sardinia margin, the opening of the Balearic back-arc basin, and the Adria-Africa-verging orogenic wedge. Some differences can be observed between the southern Apennines and Sicily. Even though the original stratigraphic relationships are not well preserved, it can be assumed that lateral to these sequences, which were involved in the lower Miocene accretionary wedge, the turbiditic sequences of the Albidona flysch were deposited toward the external portions of a "pre-Irpinian Basin." This is supported by the presence of mixed siliciclastic and calciclastic sedimentation. It has been assumed that the source area was from the Apenninic platform. In fact, toward the external areas the foredeep was probably confined by a morphological high, maybe a peripheral bulge, corresponding to the Apenninic platform, which was playing the role of foreland during the early Miocene. Toward the internal areas, the Albidona flysch laterally graded into the coeval Troina-Tusa flysch succession, as frequent volcanoclastic horizons demonstrate. Contemporaneously, during the Burdigalian, in the areas of the Ionian foreland and in part on the carbonate platform itself, the pelitic-quartzarenitic sequence of the Numidian flysch was deposited. In Sicily, the Africa foreland-foredeep system hosted extensive Numidian-type sedimentation, and glauconitic calcarenites and marls were deposited in the outermost "epicontinental" sector.

The Tyrrhenian Stage

From the time of the Burdigalian-Langhian boundary depositions, the Panormide-Apenninic platforms were stripped off from their basement and were thrust over the Ionides. Later the Ionides suffered a general décollement and overrode the external thrust system, with comsumption of the Paleo-Ionian crust originally interposed between the continental crusts. In the Calabrian arc, where the foreland is represented not by a continental crust but by the Ionian oceanic crust, the Ionian pelagic sequence was stripped off from its subducting oceanic basement and was transported eastward, forming most of the external wedge of the Calabrian arc.

In the southern Apennines, the late Miocene external flysch was deposited in a basinal area, the Irpinian basin (Fig. 5D), inherited by the Ionides (Lagonegro sequence). At that time, this basin represented the Ionian foredeep, with an inner tectonic wedge in which it is possible to distinguish at least three areas: the most internal area, characterized by satellite deposits resting unconformably upon the nappes of the chain; marls and sandstones in an intermediate position and with a general continuity on top of the Numidian flysch; and an external area with mixed siliciclastic and carbonate sediments, the latter fed by the Apulian area. The topmost Tortonian levels of these foredeep deposits are tectonically overlain by a further nappe of Tethydes that testifies to the involvement of the Irpinian basin in the Ionian subduction. This marked the consumption of the oceanic crust of part of the Ionian Paleo-basin and thus the beginning of the phase that led to the opening of the Tyrrhenian back-arc basin and the emplacement of the Aeolian volcanic island arc. On the African foreland, the crustal lineaments inherited from the Mesozoic paleogeography show an oblique direction with respect to that of the deformation front of the chain, facilitating its advance and causing a diachronous collision from west to east (Fig. 5D). This is expressed in the indentation of the continental margin and the formation of a transcurrent junction oriented about northwest-southeast, which has been active since early Pleistocene times and testifies to the cessation of the subduction process at this time in the southern Apennines and in central–western Sicily (Fig. 5E).

CURRENT GEODYNAMICS AND CONCLUDING REMARKS

In the southern Apennines as well as in Sicily, the regional architecture is represented by the allochthonous edifices of the Calabride chain and the Apenninic-Maghrebian chain, which consist of roof thrust systems underlain by a compressive rooted structure of the inner margin of the Afro-Adriatic platforms. Where the younger deformation process occurred, these deep-seated carbonate thrust systems belonging to the external thrust system are mostly constituted by reverse faults of relatively modest horizontal displacements. Only the Monte Alpi unit in the southern Apennines, the Monte Kumeta–Monte Busambra ridges in Sicily, and the "transcrustal" thrust fault (Finetti et al., 2005a,b) connected to the modern foredeeps have relevant displacement.

The integration of geological, geophysical, and volcanological data permits a better understanding of the current tectonics of this sector of the Mediterranean area. The crustal distribution and the preorogenic paleogeography of the Paleo-Ionian and Alpine-Tethys pelagic deposits floored the oceanic or thinned crusts clearly influenced the geodynamic evolution. These areas suffered subduction phenomena, and three orogenic stages have been recognized. A few features indicative of the Alpine stage have been detected in the CROP-Mare seismic lines in the Tyrrhenian Sea between Sardinia and northwestern Sicily. They can be correlated with those observed in western Calabria and in the Alpine Corsica. Moreover, these remains of an old Eo-Alpine chain provide valuable information that allows us to estimate the timing and dimension of the subsequent Tyrrhenian Sea opening. The Oligocene–early Miocene Balearic stage is well defined by tectonostratigraphy, by the structural features, and by geophysical and volcanological data. This stage is characterized by the Corsica-Sardinia rotation, by the opening of the back-arc Balearic basin, by the closure of the Alpine Tethys, and by the Afro-Adriatic-verging orogen.

The present-day setting of the structural units was in place by the Tyrrhenian stage. It commenced in the middle Miocene and is contemporaneous with the onset of Tyrrhenian back-arc basin development. Transport of the Panormide-Apenninic platforms onto the Ionides, which in turn overrode the external thrust system, was instigated by the subduction of intervening sectors of Paleo-Ionian oceanic crust and by the successive deformation of the inner margin of the Afro-Adriatic foreland.

The seismic lines reveal that a collisional setting can be recognized in the Tyrrhenian off-shore areas of both northern Sicily and the southern Apennines. In fact, a collisional continental crust has been detected and is interpreted as the original basement of the Panormide-Apenninic platforms that crops out in Sicily and the southern Apennines.

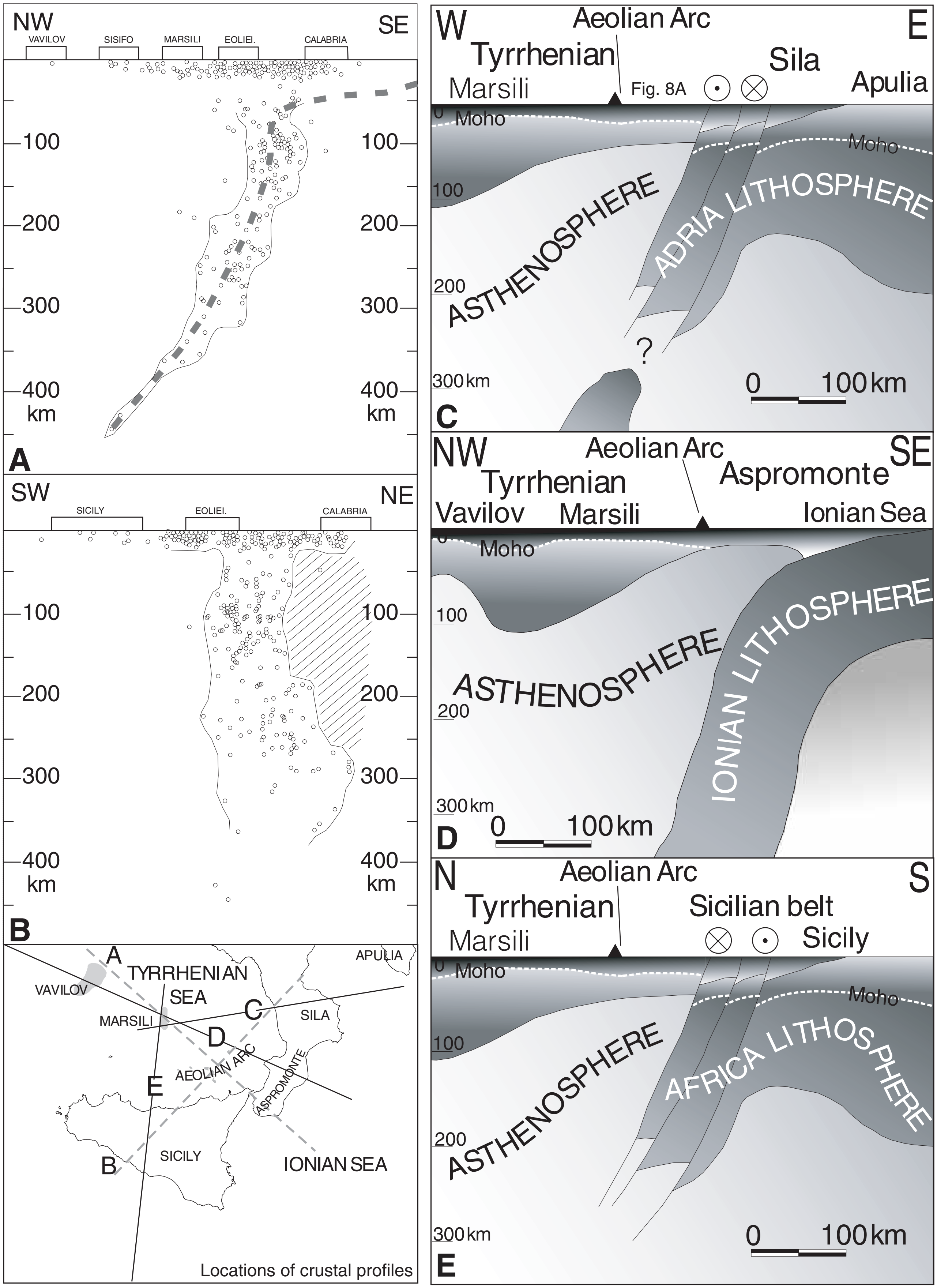
The CROP M-6B section clearly shows that the collisional crust in the Apenninic off-shore area (the Etrurian block of Finetti et al., 2005a) belongs to the Adria plate. During the early Pliocene it collided with a steep Apulian slope, generating a regional thrust fault that gave rise to the Monte Alpi tectonic unit in the external thrust system. This was acompanied by a marked component of left strike-slip motion consequent to the oblique tectonics. "Monte Alpi–like" faults, similar to the present-day example of the southern Apennines, are observed in the CROP profile sections covering northwest Sicily. Here the duplexed upper crust belongs to the Africa margin in the zone close to the subducted Ionian slab.

The latter is more or less comsumed along the peri-Tyrrhenian margins, except in southern Calabria. The surficial expression of the present collisional stage in Sicily is the right transcurrent south Tyrrhenian system. Further evidence is a general out-of-sequence thrusting that affects the present-day mountain chain of Sicily. The remains of a Paleo-Ionian slab, probably deactivated, are detected by north-south-oriented offshore seismic lines close to the Palermo coastline. Moving progressively toward eastern Sicily, the same old slab is recognizable in onshore seismic lines. To the east of the Vulcano line, in northeastern Sicily and southern Calabria the seismic imaging of the subducted upper Ionian slab is immediately evident (Fig. 6). No collisional setting occurs here, where the foreland is represented not by a continental crust but by the Ionian oceanic crust.

A similar but mirrorlike structural feature characterizes the Tyrrhenian margin of the southern Apennines. Here, a northwest-southeast-oriented fault system with a sinistral strike-slip component is considered to represent the effect of the collisional setting in this sector and of differential movements with respect to the Calabrian segment guided by the slab retreat.

The Tyrrhenian sector located between the abyssal plain and the coastline of Sicily, Calabria, and the southern Apennines corresponds to a paleo-forearc basin developed since the late Miocene above the back-stop of the chain (the collisional crust of Fig. 3) and the accretionary wedge (the Calabrian arc). The deep seismicity of the Tyrrhenian Sea confirms the presence of a northwestward subduction slab (Giardini and Velonà, 1991; see Fig. 6B), but the subduction process of the Ionian crust beneath the Calabrian arc is quite complicated due to the presence of continental crust (Africa to the south and Adria to the north) that collided against the back-stop of the entire orogenic system beginning in late Tortonian times. In particular, the absence of earthquakes up to 200 km below northern Calabria (Fig. 6B, dashed area) implies the presence of Tyrrhenian asthenosphere and the detachment of oceanic lithosphere deeper than 200 km. Figure 6C depicts the geodynamic setting along a lithospheric cross-section and the involvement of the Adria continental crust. The crustal structures below southern Calabria (Fig. 6D) are otherwise linked to a subducted lithosphere, while on the Sicilian side the collision between the orogenic back-stop and the Africa continental crust has given rise to a transpressive collision with dextral movements (Fig. 6E).

In conclusion, after the late Miocene–Pliocene development of a forearc basin in the southern Tyrrhenian sea (Fig. 7A), the evolution of the region was linked to the retreat of the Ionian subduction hinge (Malinverno and Ryan, 1986; Patacca and Scandone, 1989) and to the roll-back of the African and Adriatic


NW
SE
VAVILOV
SISIFO
MARSILI
EOLIEI.
CALABRIA
100
200
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km
A
SW
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SICILY
EOLIEI.
CALABRIA
B
A
TYRRHENIAN
SEA
VAVILOV
APULIA
C
MARSILI
SILA
D
AEOLIAN ARC
ASPROMONTE
E
B
SICILY
IONIAN SEA
Locations of crustal profiles
W
Aeolian Arc
E
Tyrrhenian
Sila
Marsili
Fig. 8A
Apulia
Moho
ASTHENOSPHERE
ADRIA LITHOSPHERE
?
300 km
0
100 km
C
NW
Aeolian Arc
SE
Tyrrhenian
Aspromonte
Vavilov
Marsili
Ionian Sea
ASTHENOSPHERE
IONIAN LITHOSPHERE
D
N
Aeolian Arc
S
Tyrrhenian
Sicilian belt
Marsili
Sicily
AFRICA LITHOSPHERE
E

Figure 7. Geodynamic evolution in space and time of the orogenic belt during the Tyrrhenian stage. (A) Late Miocene–middle Pliocene retrodeformation has occurred. The back-stop in Sicily was blocked after the middle Pliocene due to the continental collision with the African crust. (B) The roll-back of the African crust has caused collapse of the Tyrrhenian margin and the uprise of out-of-sequence crustal thrusts, while the southeastward retreat of the subduction hinge has caused segmentation of the ancient back-stop, which is fronted by tear faults. (C) Data derived from analysis of the magnetic basement map (Arisi Rota and Fichera, 1985) show a N70°E-oriented trend at a depth of 9 km, corresponding with the Ionian coast of Calabria. This might relate to crustal thickening and thus to the formation of a new back-stop with associated NNW-SSE strike-slip faults and N70°E-oriented normal faults. These last fault systems are the surficial expression of the new phase of south-southeastward retreat of the subduction hinge.

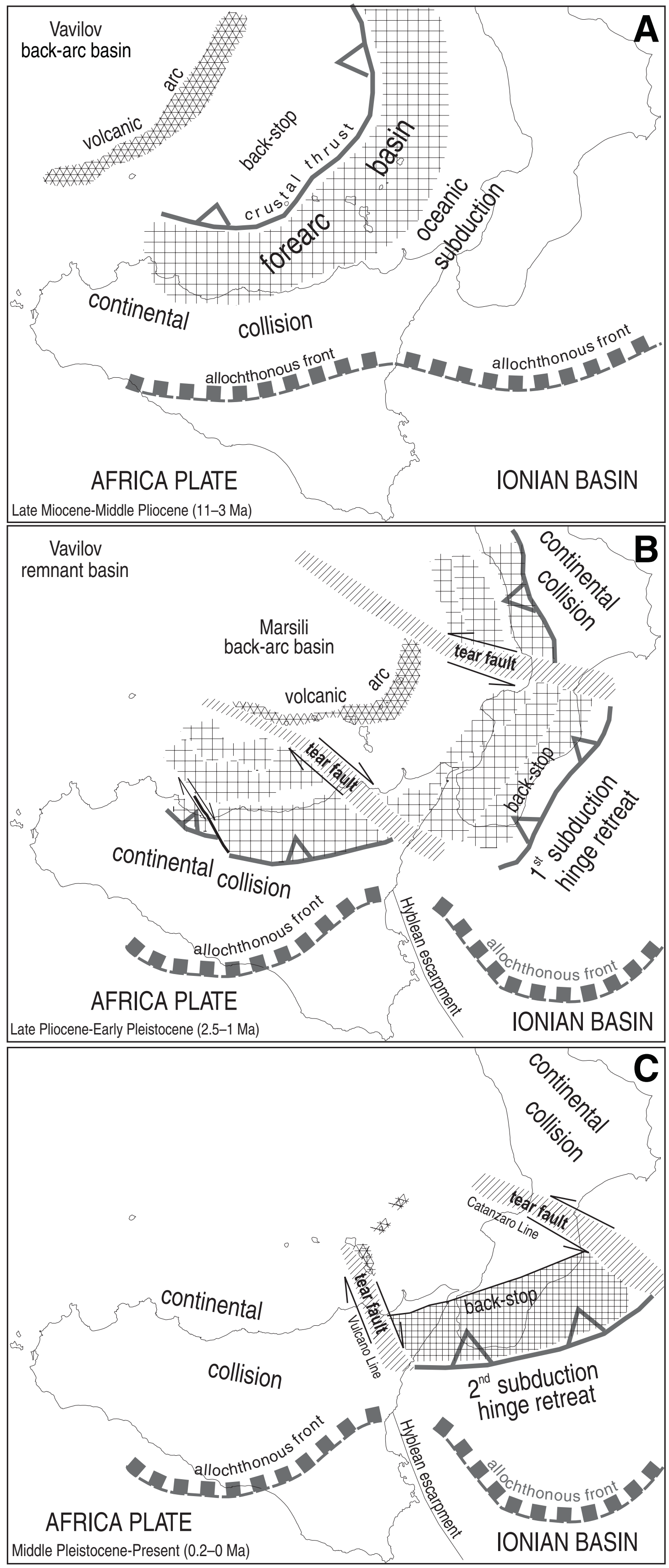

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Figure 6. Crustal profiles from the Tyrrhenian-Ionian area. The box at lower left shows the locations of the profiles. (A) Northwest-southeast cross-section from the Tyrrhenian Sea to the Ionian Sea. The circles represent the foci of deep-seated earthquakes beneath the Tyrrhenian Sea. Modified from Giardini and Velonà, 1991. (B) Southwest-northeast cross-section from Sicily to Calabria. The absence of seismicity (dashed area) below northern Calabria is well seen. (C) Lithospheric-scale cross-section of the Calabrian arc–Tyrrhenian system (modied after Gvirtzman and Nur, 2001), Tyrrhenian–northern Calabria (Sila Mountains). The Ionian slab is probably detached, as indicated by the deep seismicity of the Tyrrhenian region (Giardini and Velonà, 1991) and by the involvement of the Adria lithosphere. (D) Lithospheric-scale cross-section of the Tyrrhenian–southern Calabria (Aspromonte Mountains). Ionian lithosphere subduction is still active. (E) Lithospheric-scale cross-section of the Tyrrhenian-Sicilian belt. The presence of the African lithosphere inhibits the subduction process with the activation of a dextral transcurrent junction developed from late Tortonian to late Pleistocene times. Modified from Guarnieri (2005).

crust (Doglioni et al., 1994; Guarnieri et al., 2002). As an effect of the crustal roll-back, the sector containing the forearc basin collapsed from the late Pliocene onward to form the present peri-Tyrrhenian margin (Guarnieri, 2005). Since late Pliocene–early Pleistocene times, an early southeastward migration of the subduction hinge has been accompanied by the development of N120°E-trending tear faults and northeast-southwest-trending extensional systems (Fig. 7B). NNW-SSE-trending tear faults (the Volcano and Catanzaro lines) and N70°E-trending collapse systems formed during middle–late Pleistocene times possibly represent the response to a second SSE-ward retreat of the subduction hinge that led to the structural reorganization of a new back-stop and a corresponding collapse behind it (Fig. 7C).

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