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On the Mesozoic Ionian Basin

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SUMMARY

New seismic reflection profiles of the Italian deep crust project CROP provide new insights on the structure of the Ionian sea. In spite of the Apennines and Hellenides Neogene subduction zones, two conjugate passive continental margins are preserved at the margins of the Ionian sea, along the Malta escarpment to the southwest and the Apulian escarpment to the northeast. The Ionian sea is likely to be a remnant of the Mesozoic Tethys Ocean, confined by these two conjugate passive continental margins. The transition from continental to oceanic crust appears sharper to the northeast than to the southwest. The basin between southeast Sicily and southwest Puglia was about 330 km wide and suggests a low spreading rate. The inferred oceanic ridge should have been flattened by thermal cooling and buried by later sediments.

Based on stratigraphic and structural constraints to the north in the Apennines belt, the ocean continued to the northwest. This palaeogeography is supported by the seismicity of the Apennines slab underneath the southern Tyrrhenian sea, which implies downgoing oceanic lithosphere. The adjacent absence or paucity of deep seismicity does not imply absence of subduction, but rather it can be interpreted as due to the more ductile behaviour of the subducted continental lithosphere. Surprisingly, we note that where the oceanic inherited basin is subducting underneath the Apennines, in the hangingwall of the subduction hinge there are outcropping slices of continental crystalline basement previously deformed by the Alpine orogen.

Key words: Ionian sea, Mediterranean, Mesozoic, oceanic crust, passive margin.

INTRODUCTION

The Ionian sea is located in the central-eastern part of the Mediterranean Basin, bordered by southern Italy to the west and north, Greece to the east, and offshore Libya to the south (Fig. 1). It is a deep sea (in many places below 3000 m). Important geophysical studies on the Ionian sea have been performed during the last three decades (Hinz 1973; Panza & Mueller 1979; Farrugia & Panza 1981; Makris 1981; Calcagnile *et al.* 1982; Finetti 1982, 1985; Makris *et al.* 1983, 1986; Morelli 1985; Leister *et al.* 1986; Della Vedova & Pellis 1989; Ferrucci *et al.* 1991; Mongelli *et al.* 1991; de Voogd *et al.* 1992; Cernobori *et al.* 1996; Piromallo & Morelli 1997). In contrast, few papers have described and interpreted the geological and geodynamic evolution of the Ionian sea, owing to the deep-water conditions (Selli 1962). The ODP sites located in this basin were very few and too superficial (Ryan *et al.* 1973). Based on gravity, seismic refraction and reflection data, the crust is considered to be between 15 and 20 km thick (Locardi & Nicolich 1988; Nicolich 1989; De Voogd *et al.* 1992; Scarascia *et al.* 1994).

The Ionian Sea represents a key area for the understanding of the evolution of the Mediterranean geodynamics, both for the Apennines and Hellenic subduction zones (Scandone 1980; Angelier *et al.* 1982; Royden *et al.* 1987), and for the Mesozoic Tethyan palaeogeography (Bernoulli *et al.* 1979; Bernoulli & Lemoine 1980; Dercourt *et al.* 1986; Lemoine *et al.* 1986). This basin has been considered by Le Pichon (1982a) as a land-locked basin or a trapped crust (Letouzey 1986). In spite of this crucial location and of the several studies, we still have several doubts about the nature and evolution of the Ionian sea. There are papers that have described its oceanic nature (Finetti 1982; De Voogd *et al.* 1992; Finetti *et al.* 1996; Stampfli *et al.* 1998), but there are also articles which alternatively propose that the Ionian Basin is of denser continental crust (Farrugia & Panza 1981; Calcagnile *et al.* 1982) or a highly reflective interval within the lower crust (Cernobori *et al.* 1996).

The Ionian sea and its relationships with the surrounding areas is crucial in understanding the processes that controlled the Apennines subduction zones which consumed different lithospheres of the foreland. It is evident that the largest south-eastward advancement of the Apennines accretionary wedge

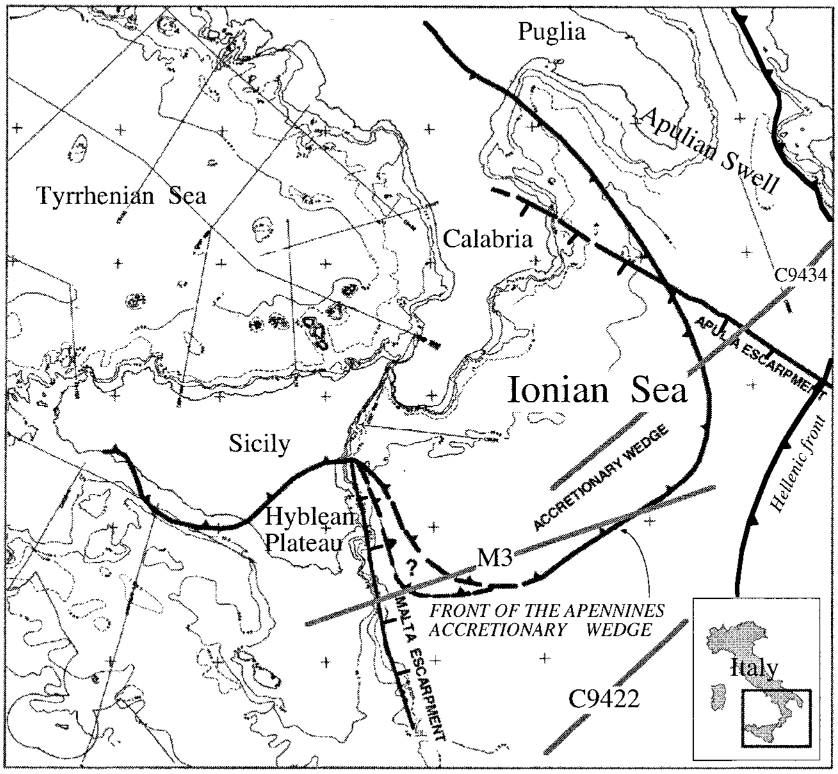

Figure 1. Locations of the seismic sections used in the paper.

occurs in the Ionian sea, offshore Calabria, and the largest expansion of the Tyrrhenian sea is located right behind to the west of the Calabrian arc (Malinverno & Ryan 1986; Doglioni 1991). In contrast, in the adjacent parts to the north of the Ionian sea in the southern Apennines, and to the southwest, in Sicily, the Apennines are less advanced towards the foreland and the Tyrrhenian backarc extension is less pronounced. Additionally, the front of the Hellenic arc (that is, the Mediterranean ridge) is more advanced towards the southwest, corresponding to the deep Ionian Basin.

Several authors described the passive continental margin of the Malta escarpment (Cita *et al.* 1981; Scandone *et al.* 1981; Casero *et al.* 1984; Charier *et al.* 1987; Cinque *et al.* 1993; Hippolyte *et al.* 1994). However, it was not comprehensively described as the conjugate margin of the Apulian swell on the other side of the Ionian Sea. In this research we want to test whether the Malta escarpment offshore east Sicily and the Salento–Apulian offshore southwest Puglia (Rossi & Borsetti 1974; Sorel 1976; Auroux *et al.* 1985; Charier *et al.* 1988; Ciaranfi *et al.* 1988; Ricchetti *et al.* 1988; Favali *et al.* 1990; Gambini & Tozzi 1996) are two conjugate passive continental margins of Triassic–Cretaceous(?) age, separated by a basin, i.e. the Ionian Ocean.

The Malta escarpment (Fig. 1) is a physiographic feature which has been tectonically controlled since Triassic times. Rocks dredged on the Malta escarpment span from the Mesozoic to the Tertiary (Cita *et al.* 1981; Scandone *et al.* 1981). The pre-Cretaceous lower fault systems (Casero *et al.* 1984) can be correlated with the evolution of a Mesozoic continental margin (Charier *et al.* 1987). Post-Tortonian and Late Pliocene–Pleistocene extensional tectonic reactivation yields high angle and listric characteristics of the normal faults in the eastward-tilted blocks (Torelli *et al.* 1998). Depositional geometries of pre-Messinian rocks prograde towards the Ionian Sea to the east.

Our main goal is to show a few new details and a new interpretation to be added to the debate on the origin of the Ionian Sea, based on new seismic lines acquired by CROP (CROsta Profonda, the Italian deep crustal project founded by CNR, ENI-Agip and Enel), tied with geophysical industrial data and inland field observations.

GEODYNAMIC SETTING

The Ionian abyssal plain (Bigi *et al.* 1989) is surrounded by a variety of geodynamic settings (Boccaletti *et al.* 1984). The Ionian lithosphere is subducting underneath Calabria to the northwest (Caputo *et al.* 1970, 1972; Gasparini *et al.* 1982; Cristofolini *et al.* 1985; Selvaggi & Chiarabba 1995; Mele 1998). The associated accretionary wedge advanced in the Ionian Sea (Tramutoli *et al.* 1984; Pescatore & Senatore 1986; Senatore *et al.* 1988; Doglioni *et al.* 1999), mainly involving the sedimentary cover on top of it (Finetti 1982). Very shallow décollements deform the Messinian evaporitic sequences, leaving the underlying crust mainly undisturbed. To the east, the Ionian lithosphere is subducting underneath Greece (Le Pichon & Angelier 1979; Le Pichon 1982b; Christova & Nikolova 1993). The southern and southwestern margins of the Ionian Sea are the areas which have not yet been involved in Tertiary and Quaternary shortening of the Apennines and Hellenic subduction zones (Fig. 1). There, the original shape of the Ionian margins may be more easily studied and they show morphology, water depth and geophysical signatures of passive margin style. The Bouguer gravity map (Fig. 2) shows values mainly between 130 and 250 mGal in the Ionian abyssal plain;

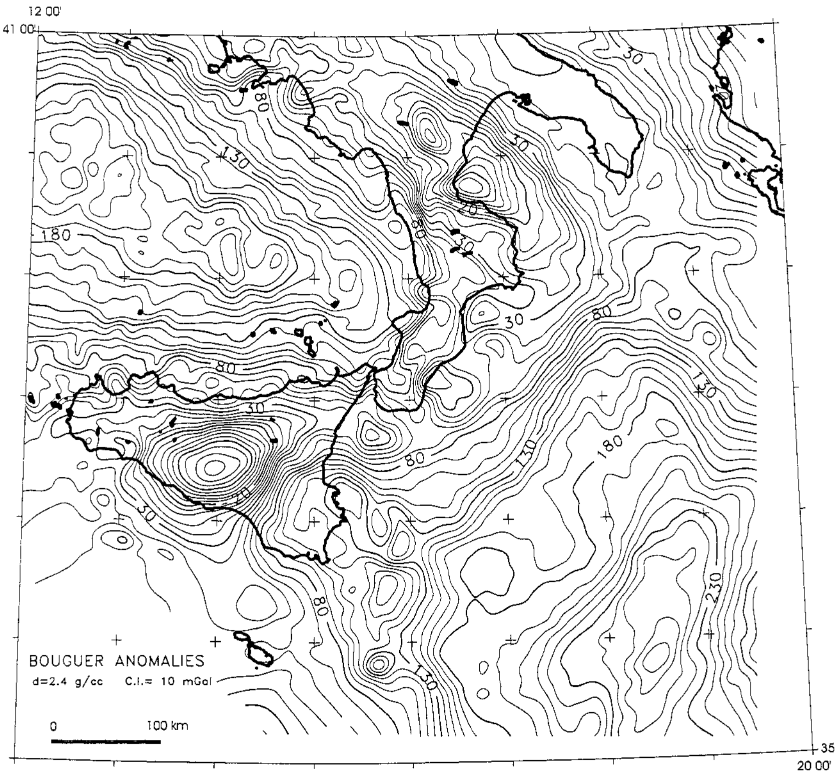

Figure 2. Gravimetric map of the Ionian Sea, courtesy of ENI-Agip.

the values decrease moving underneath Calabria to between 20 and 30 mGal due to the subduction of the Ionian lithosphere. Della Vedova & Pellis (1989) described low heat flow values (30–40 mW m^{-2}) in the Ionian Basin (Fig. 3) and proposed an early Mesozoic age for the oceanic crust.

Ciminale & Wasowski (1989) described the Hyblean plateau (or Ragusa plateau) magnetic anomaly, and compared it with the East Coast magnetic anomaly of the eastern US Atlantic passive continental margin, where this anomaly is interpreted as related to magmatic intrusions. Along the Malta escarpment in other CROP seismic reflection profiles (C9421, M23) a huge intrusion may be inferred (Catalano *et al.* 2000).

In the section between Sicily and Puglia, the Ionian Sea should be a complete oceanic section containing an aborted oceanic ridge of Mesozoic age. Its relief is lost by thermal cooling and hidden by thick pelagic deposits, ranging in age from Jurassic to Tertiary, and by the overlapping Apenninic thrust sheets. If this is the case, the Ionian sea would be one of the oldest oceanic crusts in the world.

THE CROP SEISMIC DATA

New seismic profiles have been acquired in the Ionian sea and other Italian seas and inland by the CROP project. In this paper we present segments of lines M3 and C9434 and the line C9422. These seismic profiles are particularly important for understanding the early history of the Ionian Sea (Fig. 1). The acquisition parameters and the entire set of seismic lines will soon be published as an atlas by the partners of the CROP project.

The first segment is along the Malta escarpment (Fig. 4), at the transition between the Sicilian mainland and the deep Ionian Basin. This topographic margin represents one of the most important features of Mediterranean geology and physiography (Scandone *et al.* 1981; Scarascia *et al.* 1994). The high topographic gradient corresponds to a major change in crustal thickness and composition (Finetti 1982). For a geological interpretation of this margin see Scandone *et al.* (1981) and Casero *et al.* (1984). The other line we show is located on the other side of the Ionian Sea, along the Apulian–Salento margin (Fig. 5), where there is a sudden submarine topographic step, separating the stratigraphic successions of the Apulian swell from the deep Ionian Basin; Fig. 6 is located halfway between the former sections (Figs 4 and 5). Fig. 7 is a further complete section of the southern part of the Ionian Sea.

A stratigraphic reconstruction of the three different sections is presented in Fig. 8, and Fig. 9 is a synopsis of the Ionian Sea based on the seismic and stratigraphic data. Seismic facies along M3 show high-frequency and good continuity patterns, and locally transparent or chaotic characters. In the central part of Fig. 4 (M3), the strong flat-lying reflectors are about 1 s two-way-time thick, which could correspond to the pre-Miocene deep-water succession on a stretched continental crust (Casero *et al.* 1984).

Upwards, the acoustic body is reflection-free or it shows a chaotic pattern, and it is topped by high-amplitude horizons with frequent diffraction. Its thickness ranges between 0.4 s in the abyssal plain and about 1 s two-way-time westwards, near to the continental rise. The body has been interpreted as consisting of Miocene clastics and Messinian evaporites (Cernobori *et al.* 1996). Thin Plio-Pleistocene cover is widespread all over the section.

The deep crustal levels eastwards of the Malta escarpment (Fig. 4) show homogeneous acoustic characteristics and constant thickness (about 1.5–2 s two-way time, i.e. 6–7 km). The

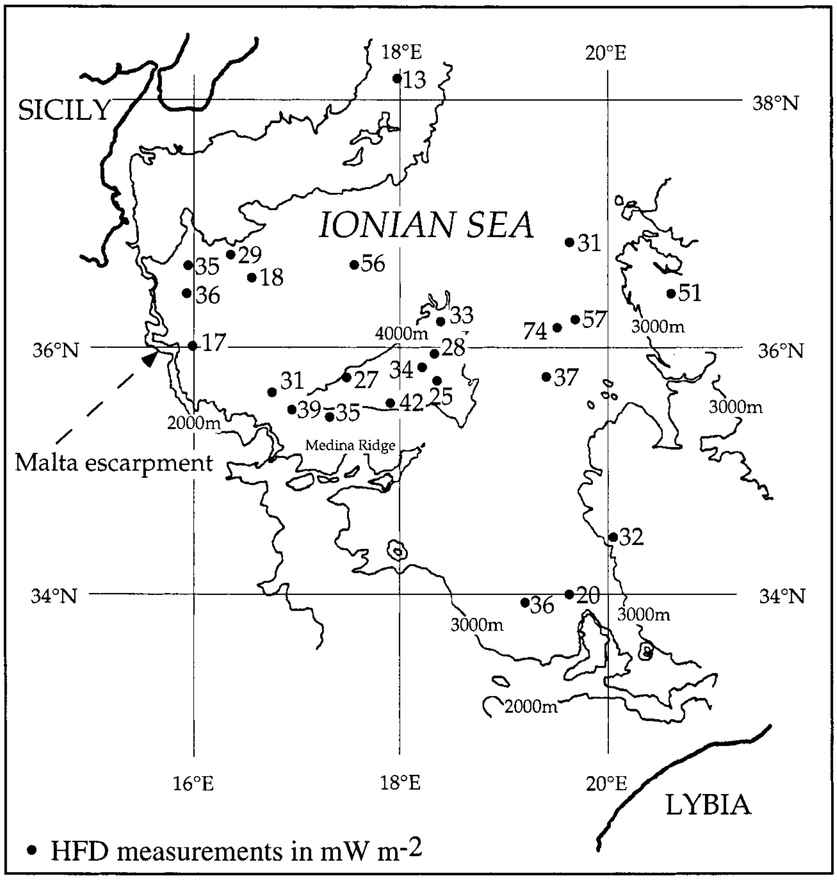

Figure 3. Heat flow values of the Ionian Sea (after Della Vedova & Pellis 1989).

reflecting band is formed by layered high-amplitude reflectors at the base of the crust (located at 8–9 s two-way time, i.e. 15–17 km, Fig. 7). The layered crust has a traveltime thickness of about 1 s. It is overlain by a seismically transparent band topped by a high-amplitude and discontinuous reflector, characterized by diffraction, located at about 7–6.5 s two-way time, shallowing towards the abyssal plain (Catalano *et al.* 2000). Similar images of the crust and depth of the Moho are described by De Chassy *et al.* (1990) in the North Atlantic margin (see their section AGC 85–1/2). However, Cernobori *et al.* (1996) disagreed with the idea that the Ionian crust has an oceanic nature, interpreting the layered reflections as the lower crust of an extremely thinned continental crust, intruded by upper mantle rocks (Makris *et al.* 1986). In Fig. 7 the layered crust shows offsets which we interpret as possible faults with extensional components.

The seismic image of the conjugate margin is seen at the Salento–Apulian escarpment (Fig. 5, line C9434) that separates the Apulia swell, composed of carbonate platform seismic facies from the Ionian abyssal plain. The escarpment view is disturbed by diffuse diffractions. However, on the right-hand side, both the top and the bottom of the Apulian Triassic–Jurassic–Cretaceous carbonate platform are easily recognizable. This is well known inland and from industrial seismic lines as a body approximately 2 s two-way-time thick (about 6 km thickness). The transition to deep-water crust is sharper than along the Malta escarpment opposite to the southwest. The crust to the southwest of the Apulian margin is poorly reflective, and the seafloor is in many places more than 3000 m deep, even up to more than 4000 m, depths which are typically oceanic.

Fig. 6 is another segment of seismic line C9434, halfway between the two former sections (Figs 4 and 5). The seafloor shows an anomalous depression which could be associated either with a confined thermal subsidence or more probably with the lateral ramps of thrust planes of the Apennines accretionary wedge. Surprisingly, however, the underlying 4 s shows crust with reflectors dipping from both sides of the section towards the central depression, but they could be multiples. The Moho depth is unclear; there are significant reflectors at about 9 s depth.

The abrupt morphologies of the Malta and Apulia escarpments indicate that there have been recent reactivations of these margins. In particular, the Malta escarpment is active in terms of seismicity and magmatism. These tectonics were interpreted by Doglioni *et al.* (1998) as being due to the right-lateral transtension generated by the differential roll-back between the Ionian sea and the eastern Sicily lithospheres.

STRATIGRAPHIC CONSTRAINTS

The area can schematically be divided into three main sectors: the Hyblean Plateau to the southwest (Sicily), the Ionian deep basin, and the Apulian swell to the northeast (Puglia) (Fig. 8). We omit, for the sake of simplicity, the allochthonous thrust sheets in the Apennines accretionary wedge.

The Hyblean plateau (Bianchi *et al.* 1987) has a Triassic–Neogene sequence more than 5 km thick, lying above a 20–25 km thick continental crust with African affinity. The main base of the sedimentary cover consists of a thick (more than 2.5 km) Upper Triassic carbonate platform (tidal flat dolomites facies),

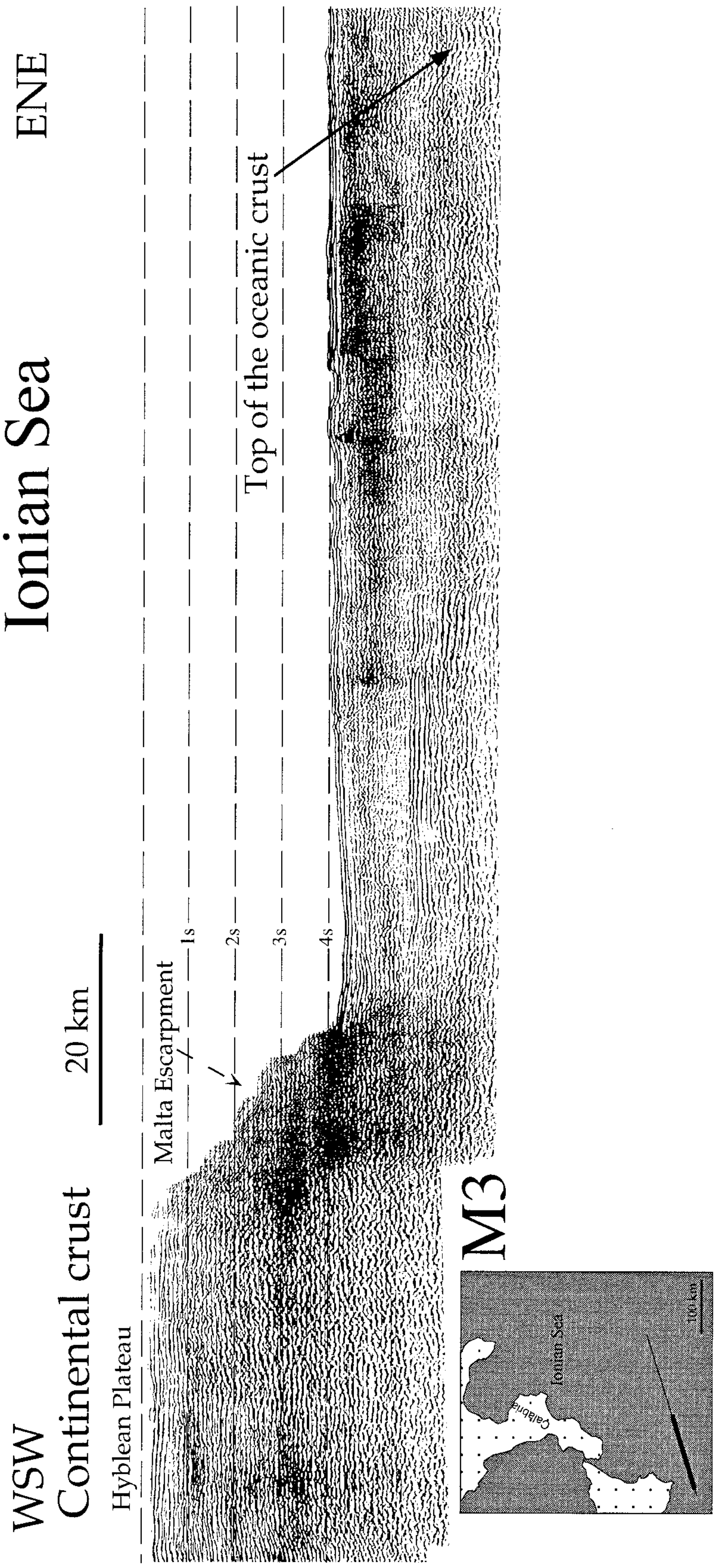

Figure 4. The Malta escarpment separates the Sicilian continental crust from the Ionian abyssal plain. It is considered to be a stretched passive continental margin.

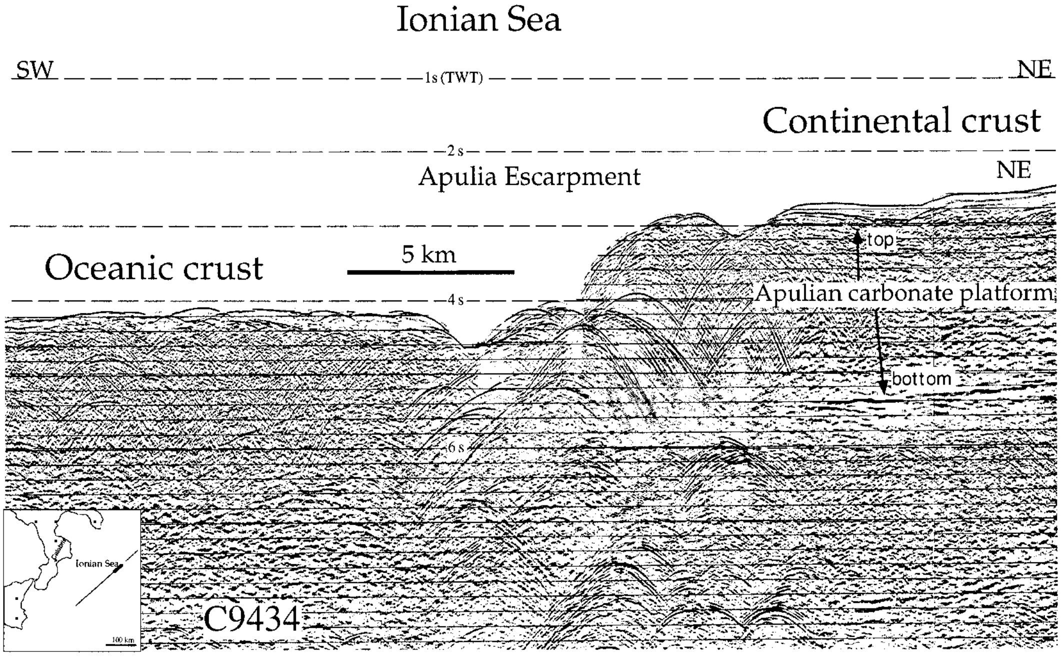

Figure 5. The Salento escarpment separates the Apulian swell from the Ionian abyssal plain. It is considered to be a stretched passive continental margin. It is sharper than the Malta escarpment and it appears as its conjugate margin.

passing to Uppermost Triassic–Lower Liassic Streppenosa basinal carbonates. The carbonate platform later drowned to pelagic facies. The eastern margin of the Hyblean plateau is the Malta escarpment (Fig. 1), where the seafloor rapidly becomes deeper towards the Ionian Sea. Clear cross-sections of the Malta escarpment were provided by Casero *et al.* (1984).

The Ionian Sea (Biju-Duval *et al.* 1982) exhibits about 4.5–5 km of sedimentary cover of seismically interpreted pelagic facies from Triassic (?) to present, apart from the Messinian evaporites, resting on top of a 'basaltic' layer of oceanic nature. Fig. 8 shows the interpreted stratigraphic column with the relative seismic velocities.

In contrast, the Apulian swell (Auroux *et al.* 1985) to the northeast (Fig. 5) lies on a crystalline continental crust. The sedimentary cover starts with a siliciclastic sequence of Late Permian–Early Triassic age, covered by an approximately

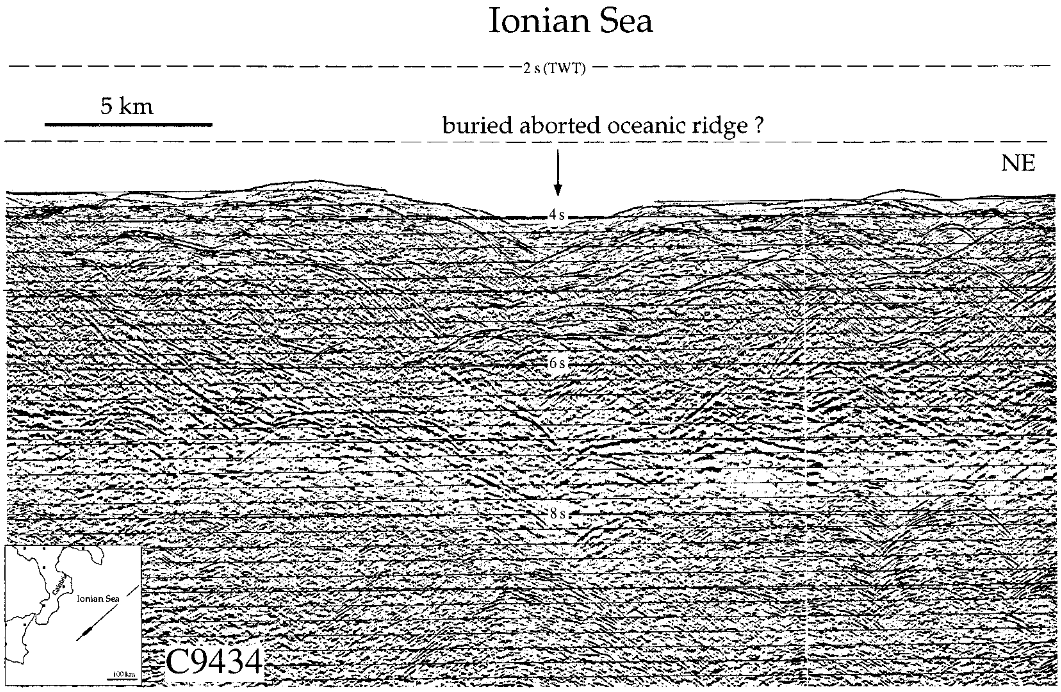

Figure 6. Halfway between the Malta and Salento conjugate passive continental margins, at about 165 km from each margin, there should be an aborted oceanic ridge. The relief of the oceanic ridge should have been lost by thermal cooling and the later burial by sediments. However, in the shallow crust (sedimentary cover), this area is affected by the front of the Apennines accretionary wedge, which may have generated rough topography.

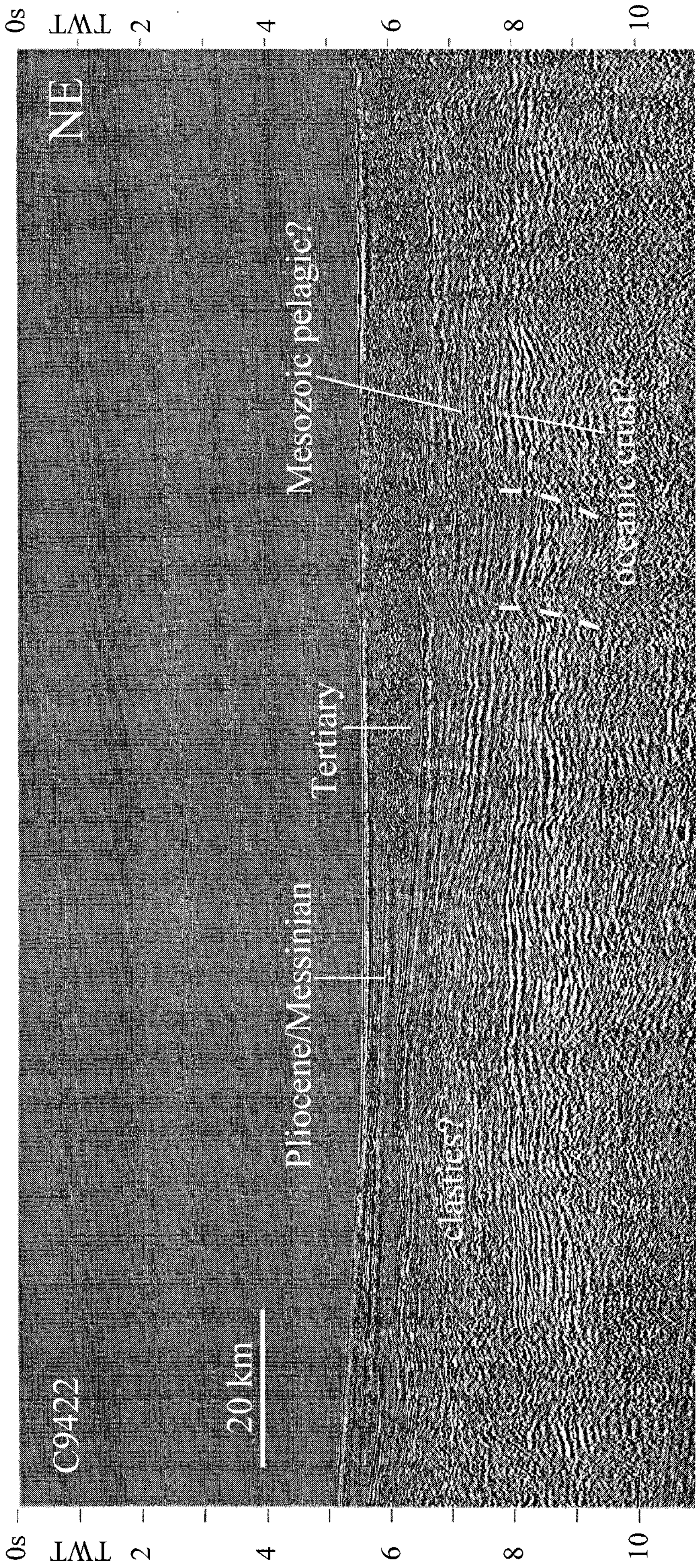

Figure 7. Seismic section C9422. Note the lens-shaped body on the left part of the section. Location in Fig. 1.

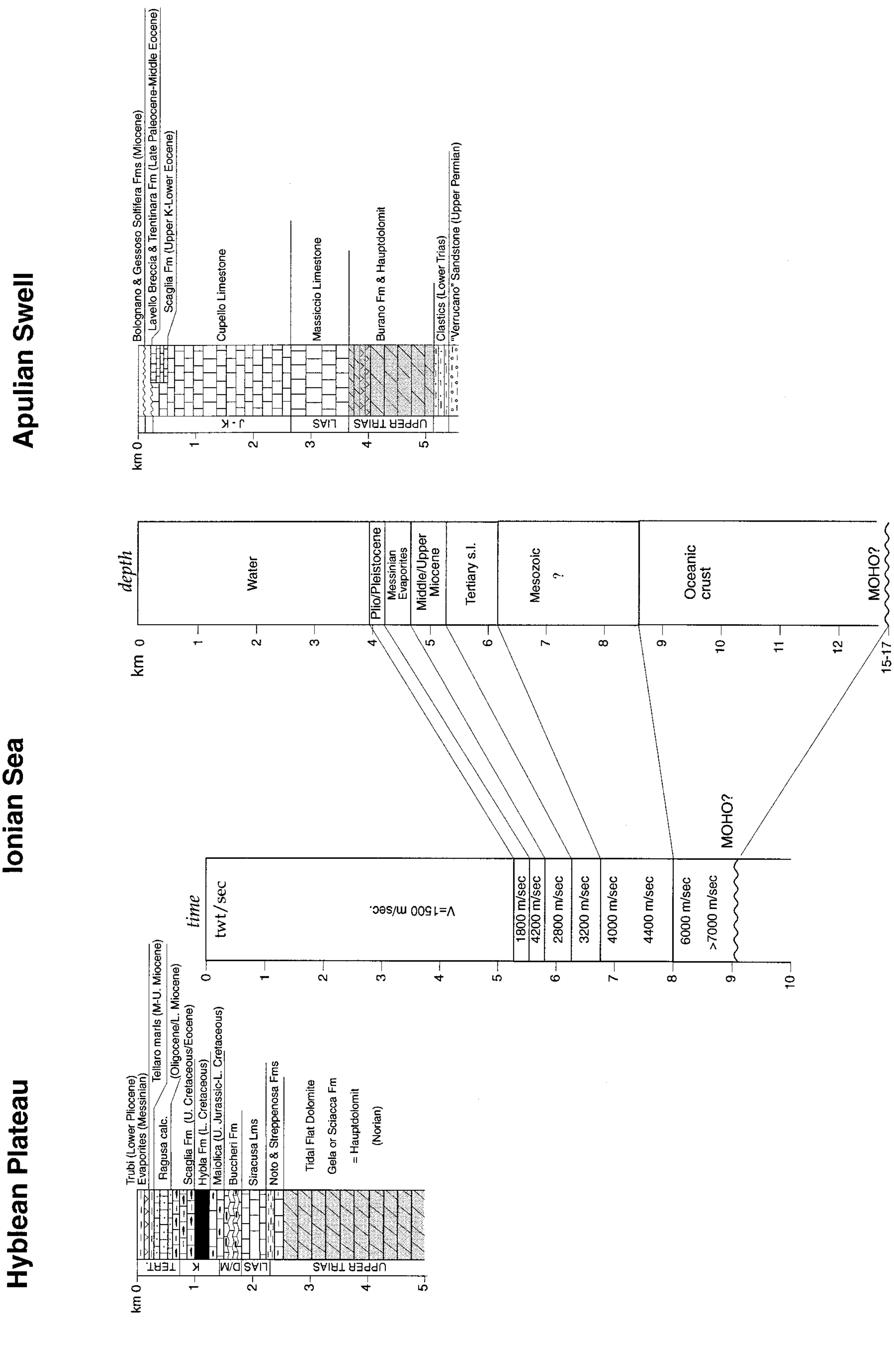

Figure 8. Stratigraphy of the three main structural areas—the Hyblean plateau, the Ionian deep basin and the Salento–Apulian swell.

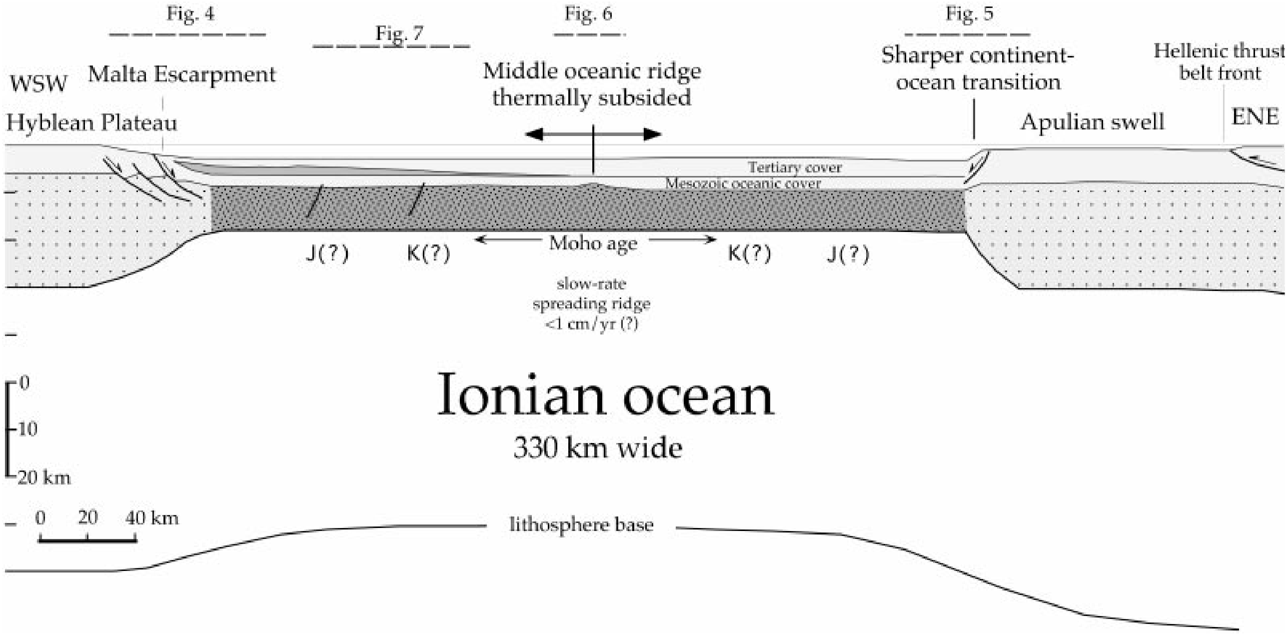

Figure 9. Reconstruction of the Ionian Ocean showing the assumed Mesozoic age of seafloor spreading. The rates of opening appear to be very low. In this interpretation, the Apulian and Hyblean plateaux were originally connected. Continental rifting might have started in Late Permian–Triassic.

5 km thick carbonate platform sequence with interbedded evaporites and a lateral pelagic transition at the top in the Late Cretaceous–Early Tertiary.

The Hyblean Plateau (Fig. 4) and the Apulian swell (Fig. 5) show typical passive margin sedimentary successions, well known inland in Sicily and the Apennines, whereas the Ionian Basin indicates a persistent deep-water environment (Fig. 7). Section C9422 (Fig. 7) exhibits a half-lens-shaped body in its southwestern segment. This body is about 100 km wide and it is marked by irregular internal reflections. We do not have any constraints on its nature; possible interpretations are conflicting, for example, either a basaltic flow or a deep-water clastic fan sourced from North Africa. The last interpretation brings to mind the Early Miocene Numidian sands of the southern Apennines (Patacca *et al.* 1992). The overlying sediments onlap the northeastern margin of the lens.

We may be tempted to link or to compare the Ionian Sea stratigraphy to the Lagonegro sequences of the southern Apennines to the north; however, several differences probably occur between the two realms. First, the Lagonegro sequence starts with relatively shallow-water facies (Monte Facito of Middle Triassic age, also containing olistholiths of Late Permian shallow-water facies). The shallow-water environment is probably associated with a continental crust of 20–30 km thickness. The overlying Calcari con Selce and the cherty Liassic Scisti Silicei more probably resemble a deep-water pelagic setting. Similar deep-water facies occur in the Imerese and Sicanian basins in Sicily. However, their shallow-water substratum constrains their position on a Permian–Triassic stretched continental crust. Therefore, the deep-water facies of the Ionian Sea cannot simply be considered as the southern equivalent of the Lagonegro sequences of the southern Apennines due to their different crustal substrate. Moreover, these Lagonegro tectonic units have overriden the Apulian platform (Mostardini & Merlini 1986) and the restoration of the thrust sheets indicates a very different palaeogeography of the Apulian, Lagonegro and Ionian Sea sequences (Zappaterra 1994) with respect to their present location in the Apennines accretionary wedge (Casero *et al.* 1988; Sella *et al.* 1988; Boccaletti *et al.* 1990; Marsella *et al.* 1995). A palaeogeographic reconstruction is proposed as shown in Fig. 10, where the Lagonegro sequences were located a few hundred kilometres westwards of their present position, before their involvement in the Apennines accretionary prism. However, the fast Liassic subsidence which generated the upward deepening of the Lagonegro and Sicilian sequences could well be associated with the opening of the Ionian Ocean.

WHAT IS THE AGE OF THE IONIAN SEA?

New lines of evidences are in favour of the old idea that the Ionian Sea is floored by oceanic crust. The Ionian Sea has a thin 8–9 km oceanic crust and 6–8 km of sedimentary cover of Mesozoic and Tertiary age (de Voogd *et al.* 1992). In their interpretation, the entire crust has a maximum thickness of 17–19 km. The interpreted oceanic crust of the Ionian Sea has been interpreted as being Early Jurassic by Finetti (1982). We interpret the top of the oceanic crust in our sections at about 6.5–8.0 s two-way time. Based on the low heat flow values in the Ionian abyssal plain at about 4000 m depth (34 mW m^{-2}), Della Vedova & Pellis (1989) proposed an age of 180–200 Myr for the oceanic embayment; the 90 km thick lithosphere (Calcagnile & Panza 1981) also supports an old age for this crust. In Sicily, deep-water pelagic Permian fauna are known throughout the Permian. Catalano *et al.* (1991) speculated that Sicily belonged either to the Permian Tethyan Ocean or to a Permian rift with thinned continental crust, a continuation of Palaeotethys further to the east. Magmatism along the Malta escarpment and on the Hyblean plateau started during Triassic times and lasted into the Tertiary. Later Pliocene and Pleistocene magmatism was emplaced along the same trend (e.g. Mount Etna).

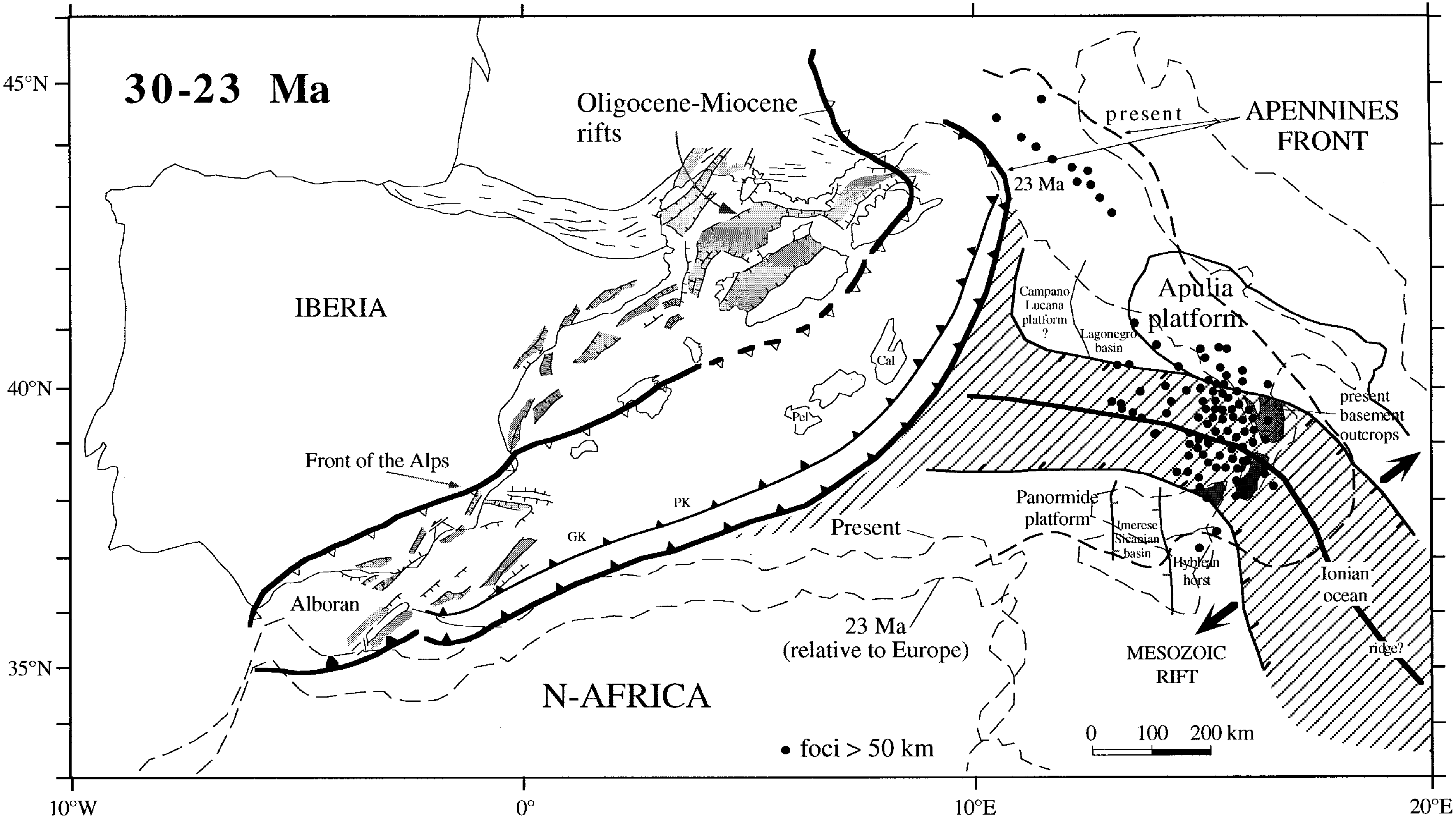

Figure 10. Late Oligocene–Early Miocene palaeogeography of the central-eastern Mediterranean, with the preserved Mesozoic palaeogeography in the Apennines foreland to the east. The 330 km wide Ionian Mesozoic Ocean had to be transferred to the west-northwest, since the restoration of the southern Apennines thrust sheets implies thinned but still continental crust to the north of the Ionian sea. The present seismicity, deeper than 50 km (after Amato *et al.* 1993) closely matches the oceanic palaeogeography. Note also the correspondence between the oceanic nature of the subducting plate and the outcrops of basement rocks in the hangingwall.

Therefore, due to the lack of direct information (magnetic anomalies, well data, etc.) on the age of the Ionian sea, we support the idea that continental rifting started in the Late Permian and Triassic, later evolving to oceanic spreading. However, we do not have reliable constraints on the end of this rifting; based only on the heat flow data and the assumed age of the sediments overlying the crust, we interpret a possible Late Cretaceous–Early Tertiary age for the abortion of oceanic spreading. Based on these assumptions and the width of the basin, we hypothesize low values of oceanic spreading (<1 cm yr^{-1}?).

The two conjugate Mesozoic passive margins (i.e. Malta and Salento) have been slightly deformed by later, mainly Neogene and Quaternary tectonics. However, we interpret the present topographic steps along the margins, between shallow water and deep water, as being mainly inherited from the Ionian Ocean rifting. The two margins have been used or reactivated as transfer zones during the larger rollback of the Ionian lithosphere subduction with respect to the adjacent continental margins. Moreover, at shallower crustal depths, these margins have also controlled the lateral advancement of the Apennines accretionary prism, where right-lateral and left-lateral transpression tectonics occurred, respectively, along the Malta and Salento margins.

IS THERE A MESOZOIC OCEANIC RIDGE IN THE IONIAN SEA?

Since the Ionian Basin is a Mesozoic Ocean with its preserved passive continental margins, we expect to recognize an oceanic ridge halfway between the two margins. The assumed ocean is about 330 km wide and therefore we checked on seismic line C9434 at about 165 km whether there is any evidence of an oceanic ridge (Fig. 6). At that point the section shows an anomalous depression of the seafloor at about 4 s two-way time and the dips of the reflectors converge below this small 3 km wide basin. However, we suspect that this anomaly could be related to the presence of folds associated with the Apennines accretionary prism, since the seismic profile is located far inside the front of the accretionary wedge (Fig. 1). Moreover, some of the signals at depth could be multiples. We also expect thermal subsidence along an aborted oceanic ridge, which would have hidden the original morphological relief of the mid-ocean ridge. The 3–6 km thick sedimentary cover above the oceanic crust generated further lithostatic subsidence, depressing and hiding the assumed oceanic ridge.

CALABRIA BASEMENT AND THE IONIAN OCEAN

It is noteworthy that the reconstruction of the northwestern prolongation of the Ionian oceanic crust based on the seismic reflection data of this study matches the occurrences of the basement rocks of Calabria and northeast Sicily (Fig. 10). Apparently, where there is downgoing oceanic lithosphere in the subduction, Alpine–Variscan metamorphic and intrusive rocks crop out in the hangingwall. The basement rocks of Calabria and Sicily (Platt & Compagnoni 1990; Bonardi *et al.* 1994) occur to the south of the Sangineto Line in northern Calabria and to the northeast of the Taormina Line in northeast Sicily (Bigi *et al.* 1989). This unexpected relationship could probably be related to the different depths of the décollement planes as a function of whether there is oceanic or thinned continental crust in the footwall of the subduction zone. In fact, the crystalline basement continues both northwest of Calabria and west-northwest of the Peloritani–Sicily outcrops, but it is buried or below sea level, as indicated by dredging in the Tyrrhenian sea (Kastens *et al.* 1988). The occurrence of basement continental rocks in the hangingwall of the subduction of oceanic lithosphere is the best evidence for an almost complete sinking of the slab, without significant accretion from the footwall to the hanging wall of the subduction of crustal material. The sedimentary cover overlying the Ionian oceanic crust is largely excluded from the subduction, being involved in the offshore accretionary wedge.

TYRRHENIAN SEISMICITY AND THE IONIAN OCEAN

There is another relevant relationship between the Ionian northwestern palaeogeographic prolongation and the seismicity. In fact, the so-called seismically active Tyrrhenian slab (Amato *et al.* 1993; Selvaggi & Chiarabba 1995) mainly follows the natural continuation of the Ionian Ocean towards the northwest (Fig. 10). This observation supports the oceanic nature of the downgoing lithosphere. However, we know that the shortening and sedimentary facies in the Apennines accretionary wedge in Sicily and the southern Apennines (respectively to the west and north of the Ionian Basin and Calabria) imply subduction of continental lithosphere stretched during the Permian and Mesozoic. These lithospheric segments adjacent to the Ionian Sea are seismically mute, or with much lower seismicity. However, the kinematics predicts several hundred kilometres (400–500 km) of shortening in the accretionary wedge of those areas. These values imply at least an equivalent amount of subduction. Therefore, the shortening which is visible in the accretionary prism where the deep-slab seismicity is lacking or attenuated suggests that subduction has occurred all along the Apenninic arc. Marson *et al.* (1995) described negative gravimetric anomalies below the southern Apennines, interpreting these data as an indication of the absence of the slab. However, these mass balances with respect to the Ionian area could be attributed to the lighter continental origin of the slab underneath the southern Apennines when compared to the heavier oceanic nature of the material to the south.

The continental lithosphere has a lower temperature for the brittle–ductile transition (300–400 °C) than the oceanic crust (500–650 °C). The paucity of deep seismicity along the southern Apennines and Sicily could be attributed to the more ductile rheology of the quartz–feldspar-rich continental lithosphere with respect to the olivine–pyroxene-rich Ionian Sea subducting underneath Calabria with a more brittle behaviour, and generating higher seismicity.

The differences in the subducting lithosphere, that is, continental below the central-northern Apennines and oceanic below Calabria, are also supported by the magmatism, which clearly shows different sources (Peccerillo 1985; Serri *et al.* 1993).

It is well established that the Tyrrhenian Basin is larger in its southern part, where the deeper Ionian Basin occurs in the foreland (Malinverno & Ryan 1986; Doglioni 1991; Faccenna *et al.* 1997). This is another indirect piece of evidence that the Ionian Sea has a different lithosphere in comparison to the Sicily and southern Apennines lithospheres.

IONIAN SEA AND TETHYS

In this paper we mainly support the idea of the oceanic nature of the Ionian sea. However, there are still several points of uncertainty, for example, the age of the opening of the basin, the anomalous geophysical signatures that are used to support the continental nature, etc. Nevertheless, there is general agreement that the Ionian Basin mainly developed during the Mesozoic, that is, as a branch of Tethys.

The reconstructions made of Tethys (Biju-Duval & Dercourt 1980; Dercourt *et al.* 1986; Ziegler 1988 and references therein) and the related Atlantic opening show that the so-called Tethyan realm was a strongly fragmented area, with isolated pieces of continental lithosphere, sometimes separated by oceanic crust, passively moving along a general E–W trend (following the transform faults of the Atlantic opening) in the western Tethys, and along a NE–SW trend in the eastern Tethys (along the Vardar subduction zone or the Cimmerian suture). When mapping the normal faults that controlled the Atlantic and Tethys opening, we note a strong coherence of data: N–S striking faults (for example, the Malta escarpment), with a variable range of 15° west or east for the Adriatic margin (Bernoulli *et al.* 1979 and Lemoine *et al.* 1986 for the European margin; Dal Piaz *et al.* 1995 and Channell & Kozur 1997 for the western Tethys; Masson & Miles 1986 for the Atlantic; Ziegler 1987 for the general area).

The Cimmerian and Vardar suture zones with a NE or NNE sense of subduction (WNW or NW trending thrust belts) have been documented as active throughout the entire Mesozoic, sometimes since the Palaeozoic (Sengör *et al.* 1984; Sengör 1984). This coincides with Tethys (both palaeo- and neo-Tethys) extensional tectonics.

The palaeogeographic reconstructions based on stratigraphic correlations have different solutions for the Ionian Sea. There are hypotheses connecting this basin to the palaeo-ocean subducted and obducted in Oman (Catalano *et al.* 1988; Bernoulli *et al.* 1990). There are interpretations of the Ionian as an embayment, closed towards the northwest; various other theories connect the Ionian Mesozoic Basin to the Ligure–Piemontese Ocean, later involved in the Alpine orogen. Some authors debate the presence of an ocean between Sicily and the southern Apennines due to the occurrence, in both areas, of the Miocene Numidian sands sourced from Africa (Patacca *et al.* 1992).

The Mediterranean orogens involved oceanic branches of the Tethys. Ophiolitic rocks of Triassic and Jurassic age and/or coeval deep-water sediments are widely distributed throughout the Mediterranean area, from Turkey into the Carpathians area, and in Sicily and the southern Apennines. The trace of the Mesozoic oceanic basins is to first approximation marked by the present shape of the Mediterranean orogens because subduction and collision zones strictly followed the pre-existing shape of the passive continental margins. Rare parts of the Tethys, not yet involved in subduction processes, are good targets for analyses of how the oceans involved and their margins were created before being lost in subduction zones or deeply transformed by metamorphism and shortening in the orogens. The Mesozoic oceanic basins probably represented extensions into the Mediterranean area of the Palaeotethyan Ocean located to the east. The rifting of Africa from North America/Europe in Triassic times gave rise to terrigenous basins and the subsequent development of evaporites and wide areas of shallow-water carbonate deposition. Accelerated subsidence in Liassic times caused foundering of carbonate platforms throughout the western Mediterranean area. The onset of oceanic rifting between Africa and North America/Europe is dated as Toarcian–Callovian by the age of the oldest sediments above the basaltic basement in the western Atlantic (Stampfli *et al.* 1998). The event is marked by accelerated subsidence throughout the western Mediterranean.

The motion of Africa relative to Europe can be established from the Atlantic spreading history (Dewey *et al.* 1989; Olivet 1996). For Jurassic and Early Cretaceous times, a sinistral transtensional motion of Africa relative to Europe is expected. This is consistent with the subsidence history and the style of faulting in the western Mediterranean, where the Triassic/Jurassic rifting between Africa and Europe occurred in an east–west sinistral transtensional kinematic framework. North Africa records the same pattern as detected in the whole of southern Europe, with north–south (N20°W–N20°E) striking normal faults and east–west (N70°–100°) strike-slip or transfer faults. In Morocco, from Late Permian until Cretaceous times, sinistral transtensional tectonics occurred along N70°–90°E basins (Gibraltar, Pay des Horst, High Atlas), whilst graben and half-graben (pull-aparts) developed *en échelon* to these features (i.e. the Middle Atlas) during the relative eastward motion of Africa with respect to Europe. The dextral relative motion of Europe relative to Africa during Late Cretaceous and Tertiary times produced the inversion of the previous structures. Former east–west-trending negative flower structures have been inverted as positive flower structures (for example, Hyblean offshore and Sicily Channel, Antonelli *et al.* 1991; Casero & Roure 1994). The greatest inversion occurred where the crust was more stretched by the earlier tectonics.

The Mediterranean region is characterized by a great lateral variability in the thickness and composition of the lithosphere (Calcagnile *et al.* 1982; Suhadolc & Panza 1988, 1989). This background is something which evolved during the 'Alpine' cycle, with a variety of tectonic regimes that affected the region throughout post-Palaeozoic times, with the opening and closing of several oceanic branches, grouped together as Tethys. It is well known that the thickness and composition of the lithosphere is a key point in controlling the rate and possibility of subduction (Cloos 1993). Consequently, the extreme lateral variability of the lithosphere of the Mediterranean, which has persisted since at least the Mesozoic up to the present, strongly controlled the relative microplate motions in the whole area (Doglioni *et al.* 1994). Note, for instance, how the Ionian subduction rapidly changes and decreases northwards and westwards, corresponding to the different compositions of the Apulian and Sicilian lithospheres. In the Adriatic and Ionian zones, the lithosphere has an average thickness of 90 km, with positive and negative oscillations of about 20 km (Calcagnile & Panza 1981; Calcagnile *et al.* 1982). The lateral variations are responsible for the irregular pattern of Tethys itself, located in between two major continental blocks (Eurasia and Africa).

The different thicknesses and compositions of the Ionian, Adriatic and African lithospheres determined the asymmetry between the northern and southern Tyrrhenian sea and southern

Apennines and Sicily. The opening of the southern Tyrrhenian sea and the shortening in the southern Apennines are much larger than those of their northern counterparts, in particular at the 41° latitude transition; this structural variation occurs where the Ionian oceanic lithosphere in the foreland to the south and the Adriatic thick continental lithosphere to the north are subducting. In this regard, the Tyrrhenian sea represents a powerful laboratory in which to investigate different styles and amounts of back-arc extension as a function of the composition and thickness of the subducting lithosphere of the foreland, that is, the Ionian, Adriatic and Sicily lithospheres.

The larger expansion of the Neogene and Quaternary Apennines arc in the Ionian Sea (Fig. 1) confirms how the Mesozoic Ionian Basin subducted and retreated faster and more easily than the neighbouring areas of Sicily and the southern Apennines (Malinverno & Ryan 1986; Patacca & Scandone 1989; Doglioni 1991; Faccenna *et al.* 1997).

CONCLUSIONS

The Ionian Sea appears to be an oceanic basin of Mesozoic age (Fig. 9). It mimics several morphological and geophysical signatures which have been described in the central Atlantic Ocean (Dañobeitia *et al.* 1995). However, there are still some anomalies in its geophysical signatures (compare Calcagnile *et al.* 1982 and De Voogd *et al.* 1992). Whatever its origin, the Ionian Sea is a rifted area whose stretched conjugate margins are the Malta escarpment to the southwest and the Apulian escarpment to the northeast (Fig. 9). The oceanic nature of the Ionian Sea would imply an aborted middle oceanic ridge located halfway between the two conjugate passive margins (Fig. 10). However, the topographic elevation of the ridge axis should have been lost by thermal cooling after ocean abortion and the later burial of Tertiary sediments. The Apennines accretionary wedge also overrode the ocean ridge zone (Fig. 6). Based on the undulating strike of the two conjugate passive continental margins, the direction of the Mesozoic extension could have been oriented NE–SW (Fig. 10).

The age of the basin is not yet well constrained. Based on the deep seafloor (>4000 m in the abyssal plain), low heat flow (30–40 mW m^{-2}, Della Vedova & Pellis 1989) and stratigraphy of the rifted margins, the rifting could be Permian–Triassic at the continental stage, evolving to oceanic spreading during the Late Jurassic–Early Cretaceous. During the Late Tertiary, the Ionian Sea looks like an aborted trapped oceanic basin.

Based on inland constraints, that is, the Sicilian and southern Apennines carbonate platform margins and adjacent basins, the Ionian Ocean continued to the northwest (Fig. 10). Since the main deformation of the Ionian area started in the late Neogene, the reconstruction at early Miocene–late Oligocene times of Fig. 10 is considered as a view of the Mesozoic palaeogeography.

The seismicity of the Apennines slab underneath the southern Tyrrhenian sea, which implies downgoing oceanic lithosphere, also supports the palaeogeographic prolongation of the Ionian Ocean towards the northwest (Fig. 10). The absence or paucity of seismicity to the north in the southern Apennines and in Sicily and their Tyrrhenian margins does not imply the absence of the Apennines slab continuity in those areas. These changes in seismicity and in several other geological and geophysical signatures may be explained by the inherited Mesozoic crustal and lithospheric differences of the downgoing foreland, that is, oceanic in the Ionian, and continental in the southern Apennines and Sicily.

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