Mem. Descr. Carta Geol. d'It.
XLIV (2004), pp.147-164
12 figg.

On the tyrrhenian sea opening
Sull'apertura del Mar Tirreno

DOGLIONI C. (*), INNOCENTI F. (**), MORELLATO C. (*),
PROCACCIANTI D. (*), SCROCCA D. (***)

ABSTRACT - The Tyrrhenian Sea is the easternmost basin of the boudinated backarc lithosphere in the hangingwall of the Late Oligocene to Present Apennines subduction, which started in the Provençal and Valencia troughs and progressively moved to the Algerian and Tyrrhenian basins. All basins and in particular the Tyrrhenian Sea are asymmetric, being more extended and magmatically intruded in the eastern side, as testified also by the higher heat flow. The Apennines slab retreated "eastward", which kinematically requires an eastward mantle flow either to compensate or push the slab rollback.

Corsica and Sardinia represent the major lithospheric boudin in the backarc basin and their crustal and lithospheric roots have an eastward offset with respect to the superficial topography, possibly related to the shear induced by the underlying relative eastward mantle flow. It is interpreted that the mantle that generated the oceanic crust of the Provençal basin was depleted and consequently it became lighter; during its eastward transit below Sardinia and Corsica the depleted mantle could have generated the Miocene uplift of the continental swell.

Fault spacing in the brittle upper crust has an average value of 4-5 km in the Northern Tyrrhenian and 4 km to 16-17 km in the southern part. Internal sub-basins developed at different bathymetries, due to variable stretching and sediment supply in the different parts of the Tyrrhenian Sea. Northern and southern Tyrrhenian basins present respectively as minimum estimates 25 and 253 km of extension, according to the larger subduction of the Ionian heavier lithosphere of the Apennines foreland. The whole Tyrrhenian basin opened obliquely to the pre-existing alpine orogen. Therefore the main Tyrrhenian architecture and magmatism seem to have been primarily controlled by the composition and thickness of the downgoing subducting lithosphere beneath the Apennines, i.e., continental in the Adriatic and oceanic in the Ionian, and the westward motion of the lithosphere relative to the mantle.

KEY WORDS: Tyrrhenian Sea, backarc basin, slab retreat, eastward mantle flow

RIASSUNTO - Il Mar Tirreno è il bacino più orientale del Mediterraneo occidentale, che è considerabile come un unico grande bacino di retroarco della coeva subduzione appenninico-maghrebide, attiva dall'Oligocene superiore all'attuale. L'estensione è iniziata nei bacini Provenzale e di Valenzia, e si è progressivamente spostata nei bacini di Algeria e del Tirreno, generando un diffuso budinaggio della litosfera. Tutti i bacini, e in particolare il Tirreno, sono asimmetrici, essendo più assottigliati sul lato orientale, come confermato anche dal maggior magmatismo e dal più alto flusso di calore. La subduzione appenninica è arretrata verso "est", il che implica cinematicamente un flusso di mantello nella stessa

(*)Dipartimento di Scienze della Terra, Università La Sapienza, Roma
(**)Dipartimento di Scienze della Terra, Università di Pisa
(***)CNR-IGAG, Roma

direzione o a compensare, o a generare l'arretramento stesso. Il blocco sardo-corso rappresenta il più grande "budino" litosferico dell'intero bacino di retroarco; le sue radici crostali e litosferiche sono spostate verso est rispetto alla topografia, probabilmente a causa del flusso relativo del mantello verso est. Si interpreta che il mantello che ha generato la crosta oceanica del bacino Provenzale si sia impoverito, e sia divenuto quindi meno denso; durante il suo movimento verso est, transitando sotto Corsica e Sardegna, questo mantello più leggero potrebbe aver generato il sollevamento Miocenico del blocco continentale.
La spaziatura tra le faglie nella crosta superiore fragile ha una media di circa 4-5 km nel Tirreno settentrionale, e di 4-5 km, e 16-17 km nel Tirreno meridionale. Vi sono sotto-bacini interni minori a batimetria diversificata a causa del diverso grado di assottigliamento, e del variabile apporto sedimentario. Il Tirreno settentrionale e meridionale hanno subito un'estensione minima rispettivamente di 25 e 253 km, in accordo con la maggiore apertura del retroarco dove in avampaese dell'Appennino è subdotta la litosfera oceanica ionica più pesante. L'intero bacino tirrenico si è aperto obliquamente rispetto al pre-esistente orogene alpino. La struttura e il magmatismo del Tirreno sembrano dunque essere stati controllati principalmente dalla composizione e spessore della litosfera in subduzione sotto gli Appennini, cioè continentale in Adriatico e oceanica nello Ionio, e dal movimento verso "ovest" della litosfera rispetto al mantello.

PAROLE CHIAVE: Mar Tirreno, bacino di retroarco, arretramento della subduzione, flusso verso est del mantello

1. - INTRODUCTION

This paper aims to contribute in unravelling the tectonic evolution of the Tyrrhenian Sea (fig. 1), providing a multidisciplinary approach, regarding its structure, magmatology and geodynamics. The Tyrrhenian basin is the easternmost sub-basin of the wider western Mediterranean backarc basin, developed since the Late Oligocene in the hangingwall of the Apennines-Maghrebides "west"-directed subduction zone, which generated the arc running from northwest Italy throughout the Italian peninsula, Sicily and the north-western margin of Africa, from Tunisia to Morocco (REHAULT *et alii*, 1984; GUEGUEN *et alii*, 1998). The other western Mediterranean sub-basins are the Alboran, Valencia, Provençal and Algerian troughs. The Tyrrhenian Sea is the recent most sub-basin, developed from Miocene-to-Present (e.g., SCANDONE, 1980; MALINVERNO & RYAN, 1986). The basin is asymmetric in any respect: the extension is larger in the south; the rifting process and the related magmatism migrated in time from west to east (e.g., KASTENS *et alii*, 1988; BIGI *et alii*, 1992; SARTORI, 1989; DOGLIONI, 1991; SAVELLI, 2002). The extension evolved to oceanization in two main areas, i.e., the Vavilov (7-3.5 Ma) and the Marsili (1.7-1.2 Ma) sub-basins (BIGI *et alii*, 1989). Subduction-related magmatism and OIB basalts coexist in the Tyrrhenian

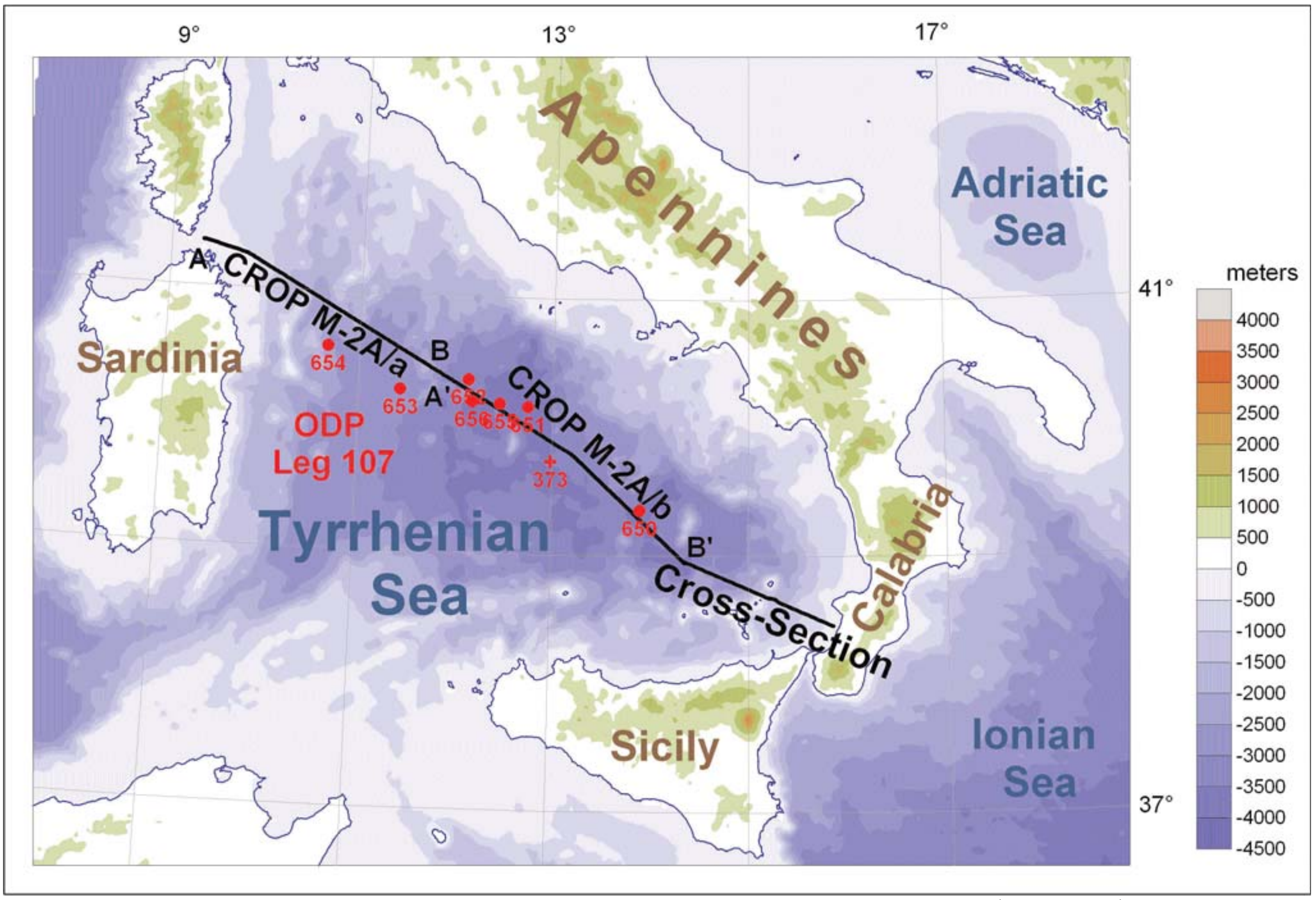

Fig. 1. - *Bathymetric map of the Tyrrhenian Sea and location of the cross-section and of the Crop seismic profiles M-2A/a and M-2A/b, interpreted in figures 3 and 4.*

basin and surrounding areas (e.g., SERRI *et alii*, 1993; SAVELLI, 2002). Researches about the geological history of the Tyrrhenian Sea have greatly improved due to some DSDP and ODP wells, seismic reflection profiles, dragging and volcanological researches (e.g., ZITELLINI *et alii*, 1986; FINETTI & DEL BEN, 1986; ELLAM *et alii*, 1988; KASTENS *et alii*, 1988; FRANCALANCI *et alii*, 1993; PASCUCCI *et alii*, 1999). Several papers proposed geophysical and geodynamic models on the opening of the basin (e.g., SCANDONE, 1980; MALINVERNO *et alii*, 1981; MANTOVANI, 1982; MOUSSAT *et alii*, 1986; FINETTI & DEL BEN, 1986; MALINVERNO & RYAN, 1986; PATACCA & SCANDONE, 1989; MONGELLI & ZITO, 1994; FACCENNA *et alii*, 1997; GUEGUEN *et alii* 1997; CELLA *et alii*, 1998; PANZA, 1998; DOGLIONI *et alii*, 1999; MAUFFRET *et alii*, 1999; PECCERILLO & PANZA, 1999).

There are several questions that are still unsolved in the knowledge of the basin, such as what is the exact relation with the Apennines subduction, what is the total extension in the different parts of the basin, when it opened, how many faults accompanied the opening, why Corsica-Sardinia uplifted during the opening of the western Mediterranean basin, why there are variations in the geochemical signature of magmatism, what is the relationship with respect to the Alpine orogen. In the following, new data are described and a few interpretations of the aforementioned themes are discussed.

2. - GEODYNAMIC SETTING

A number of different models tried to describe the process of the Tyrrhenian Sea opening. Most of them related the basin evolution to the Apennines subduction zone. Subduction of the Adriatic-Ionian plate is demonstrated by the existence of a well-defined Benioff plane under the Tyrrhenian Sea. Many authors (CAPUTO *et alii*, 1970; GASPARINI *et alii*, 1982; GIARDINI & VELONÀ, 1991; AMATO *et alii*, 1991, 1993; SELVAGGI & CHIARABBA, 1995; CIMINI, 1999; DE GORI *et alii*, 2001; SELVAGGI, 2001; PIROMALLO & MORELLI, 2003) have depicted the geometry of the subducted slab with different seismological methods. SELVAGGI & CHIARABBA (1995) have defined a continuous slab having a gentle slope down to 50 km of depth, then a rapid increase at the hinge, where the slope reaches 70° that remains constant down to 500 km. However this dip is partly computed along a section oblique to the slab, measuring a lower apparent dip.

There are a number of evidences indicating that the extension rates in backarc rifts such as the Tyrrhenian or Pannonian basins are related to the rates of subduction. The co-genetic link between the Apennines subduction and the Tyrrhenian backarc is supported by the following evidences, such as the coeval evolution of the two processes, the same "eastward" migration, the largest opening of the southern Tyrrhenian basin in correspondance of the maximum subduction depth of the Calabrian slab segment, where oceanic lithosphere is present in the Ionian foreland and it is supposed to continue northwestward at depth (CATALANO *et alii*, 2001). The co-genesis does not highlight whether the subduction generates the back-arc, or viceversa, where the rift is actively opening and subduction is a consequence of the expanding lithosphere. This last interpretation fails to explain the single polarity of the extension. Alternatively, both backarc rift and subduction are phenomena related to a third common process.

Extensional thinning of the lithosphere is often considered as related to stresses generated by boundary forces related either to slab pull or ridge push, or collapse of the orogen (e.g., FORSYTH & UYEDA, 1975; ROYDEN, 1993; PLATT & VISSERS, 1989; FACCENNA *et alii*, 2003). However, along slab compression focal mechanisms (FREPOLI *et alii*, 1996) are against the slab pull force, and the ridge push effect is too low in the Mediterranean basin. Moreover the rifting is oblique and even located far away from the pre-existing Alpine-Betic belt, supporting an independent origin from the gravitational collapse of the orogen ralated to the convective removal of its roots (DOGLIONI *et alii*, 1997). An alternative model relates rifting to the differential drag exerted by an eastward migrating mantle, providing an horizontal force able to push down also the "west"-directed slab (DOGLIONI *et alii*, 1999).

The Tyrrhenian rifting proceeded through jumps isolating thicker lithospheric swells, generating a sort of boudinage of the lithosphere (GUEGUEN *et alii*, 1997). Episodic backarc extension in the Tyrrhenian basin would suggest either that the subduction rate is not continuous or, alternatively, the stretching in the backarc is not continuous during a steady state subduction process. The average rate of the largest extension deduced by comparing the subducted slab length (>500 km), backarc basin width and its age (about 20 Ma) is in the order of about 2.5 cm/yr. The rifting opened mainly from W to E in most of the basin, but in the south-eastern part it deviated to SE since late Pliocene (?). This could be related to the encroachment of the Adriatic thick continental lithosphere east of the southern Apennines which slowed that segment of the subduction (DOGLIONI *et alii*, 1994). Then the rollback concentrated to the southeast toward the inherited Mesozoic Ionian ocean basin (CATALANO *et alii*, 2001) and to the northeast in the central-northern Adriatic Sea. The Tyrrhenian basin has a triangular shape with a tight angle in the north. The kinematics of the Apennines-Tyrrhenian system predict diffuse right-lateral transtension in the NW-SE-trending central-northern part, and left-lateral transtension in the E-W-trending southern part, north of Sicily. This tectonic setting is conjugate to the diffuse left-lateral transpression in the NW-SE-trending central-northern part of the Apennines, and right-lateral transpression in the E-W-trending southern part (DOGLIONI, 1991). The migration of the Apennines arc during the last 30 Ma has been computed to more than 700 km, a value about five times higher than the contemporaneous N-S convergence (130 km) of Africa (Tunisia) relative to Europe: this indicates that i) the Apennines arc migration and its related Tyrrhenian backarc opening have independent origin from the Africa-Europe relative motion (GUEGUEN *et alii*, 1998) and ii) the Apennines-Tyrrhenian arc is rather slightly deformed in the southern arm by the Africa impingement.

The Adriatic microplate subduction initiated in the Late Oligocene-Early Miocene and developed to the east of the former Alpine-Betics belt, along its retrobelt. The Apennines accretionary prism formed in sequence at the front of the Alpine retrobelt. The Apenninic back-arc extension migrated eastward and boudinated the former Alpine nappe stack (DOGLIONI *et alii*, 1998). Kinematics and geophysical data support the presence of an eastward migrating asthenospheric wedge at the subduction hinge of the retrating Adriatic plate (DOGLIONI, 1991; GUEGUEN *et alii*, 1997). Mantle tomography and Q values confirmed the presence of a shallow asthenosphere below the western Apennines (PIROMALLO & MORELLI, 2003; MELE *et alii*, 1997).

Rifting initiated in the Upper Oligocene in the Liguro-Provençal basin to the west of the Corsica-Sardinia, floored by oceanic crust 19-15 Ma ago. The rifting jumped east of Corsica and Sardinia proceeding by steps and generating in the southern Tyrrhenian few major sub-basins, marked by homonymous volcanoes, i.e., Magnaghi, Vavilov and Marsili (fig. 2).

Basalts at the Mt Vavilov are OIB-MORB type with an age of 4.1 Ma (SARTORI, 1989), while the basalts of Mt. Marsili are also calc-alkaline (BECCALUVA *et alii*, 1990), and the upper-lying sediments have an age of 1.8 Ma (KASTENS *et alii*, 1988) indicating a young basaltic crust.

The Tyrrhenian Sea shows high Bouguer anomaly (>250 mGal) and heat flow values, both indicating shallow hot mantle and thin crust. The highest values are shifted in the eastern side, indicating asymmetry of the rift and possibly of the underlying mantle (fig. 2).

The map of the depth of the Moho (NICOLICH, 1989, NICOLICH & DAL PIAZ, 1991) shows values lower than 15-20 km for the bathial plane, and two minima of 10 km centered on the Vavilov and Marsili basins. It is worthwhile to note that these minima coincide with the highest values of the heat flow. The lithospheric boudinage proposed by GUEGUEN *et alii* (1997) is also suggested to be asymmetric by the gravimetric reconstruction of CELLA *et alii* (1998), being the continental roots of Corsica-Sardinia shifted to east with respect to the higher topography. This would confirm the presence of a migrating asthenosphere from west to east.

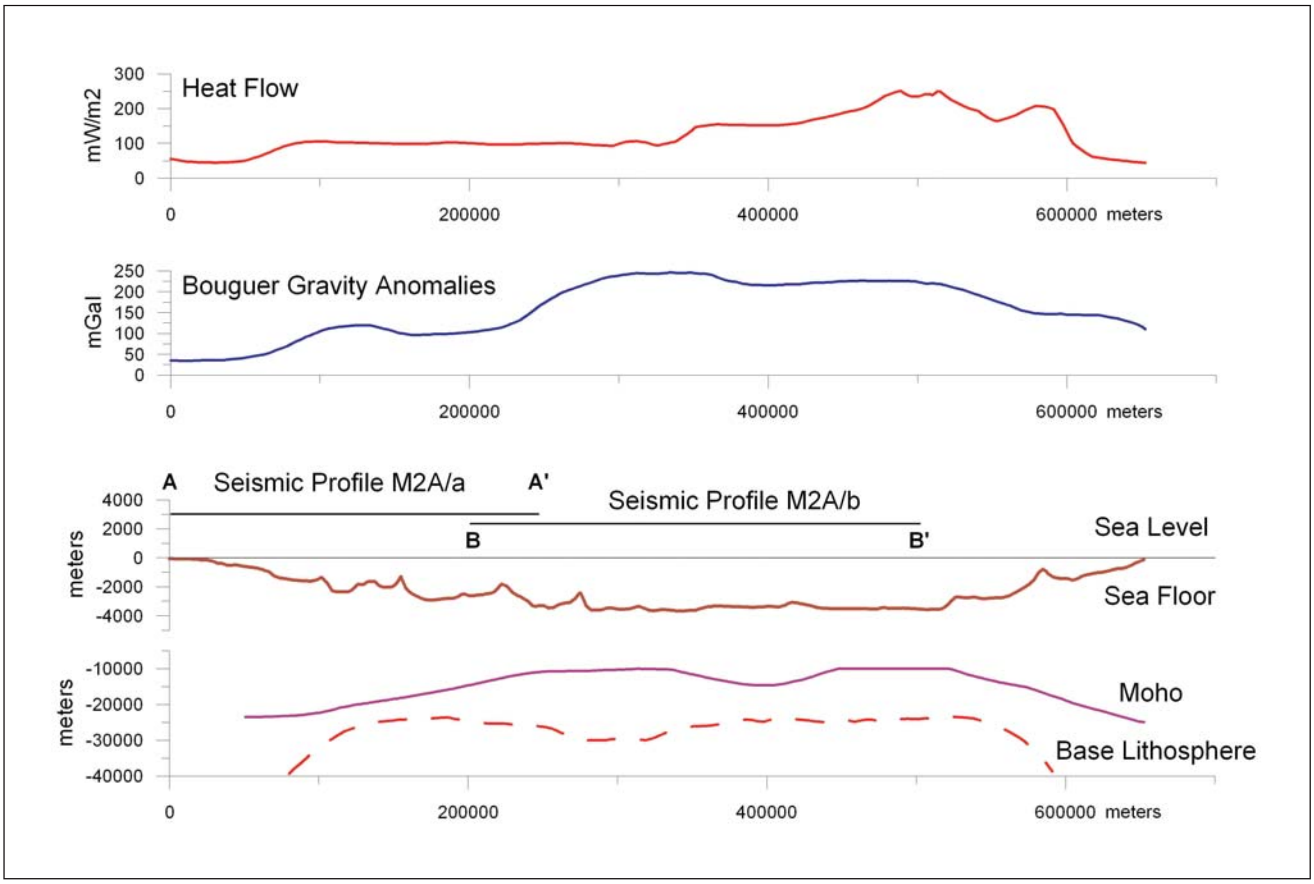

Fig. 2. - *The crustal and lithospheric structure of the Tyrrhenian Sea are shown along a regional cross-section (see fig. 1 for location) built along the* CROP *seismic profiles M2A/a and M2A/b ; heath flow and Bouguer anomalies are shown along the same cross-section.*
Data sources: Moho depth after NICOLICH & DAL PIAZ (1992), NICOLICH *(2001); base Lithosphere after* PANZA *et alii* (1992; 2003)*; Bouguer Gravity Anomalies after* MONGELLI *et alii* (1975)*; Heath Flow data after* DELLA VEDOVA *et alii* (2001). *Note the higher heat flow and gravity values in the eastern side of the basin.*

The Tyrrhenian Sea can be divided into three parts, i.e., northern, central and southern areas. The southern one (fig. 1) is the widest and more stretched area; it is the deepest part of the Tyrrhenian sea (>3500m), being subdivided into the aforementioned sub-basins. It is also the area of highest heat flow values (DELLA VEDOVA *et alii*, 1991; MONGELLI *et alii*, 1991) in some spots of the south-eastern part (>200 mW m^{-2}). The central part of the Tyrrhenian sea is rather characterized by the lowest heat flow values of the basin (~100 mW m^{-2}). Moving into the northern Tyrrhenian sea, close to Tuscany heat flow values are high again (>160 mW m^{-2}). Stretching in the Tyrrhenian sea decreases from south to north, and therefore there seems not to be a linear relation between total extension and heat flow. Asymmetric rifting and heat flow occur also in the Ligurian Sea at the northernmost tip of the Tyrrhenian Sea (PASQUALE *et alii*, 2002).

However there rather appears an evident correlation between active magmatism and heat flow, and the magmatism is directly correlated to the activity of the subduction rate and composition of the slab in the Apennines. In fact the most active part of the Apennines subduction is in the Southern Tyrrhenian-Calabria, where in the foreland there occurs the oceanic Ionian basin. Moving northward, the foreland of the southern Apennines is almost locked by the presence of the Puglia thick lithosphere (CALCAGNILE & PANZA, 1981), which is barely subducting and buckled (DOGLIONI *et alii*, 1994). This area of slow or stopped downgoing of the slab is recorded in the backarc basin where extension seems rather starved, low or absent magmatic activity, and low heat flow. The central northern part of the Apennines subduction is more lively, it generates seismicity and latent magmatism in Latium and Tuscany, and relatively high heat flow.

3. - THE CROP M2A PROFILE

A new picture of the structural setting in the Tyrrhenian Sea is provided by the new data acquired within the framework of the Italian deep crust exploration project (CROP Project). The main goal of the CROP Project was to study the crustal structure by means of near-vertical reflection (NVR) seismic as in similar projects in the USA (COCORP), in Germany (DEKORP), in France (ECORS), and in the UK (BIRPS). With this project, supported by the Italian National Research Council (CNR) and by two leading companies in the energy sector (ENI-AGIP and ENEL), more than 8700 km of seismic profiles off-shore and about 1254 km on-shore have been acquired, in the period 1986-1999.

The Tyrrhenian Sea is crossed by several CROP seismic profiles; two of them, the CROP M2A/a and M2A/b profiles, have been considered in our study (fig. 1). Both these profiles were acquired in 1991 by OGS: the first one was processed by ISMES in 1993 while the second one by OGS in 1991; the two seismic profiles present an overlap of about 30 km.

In this paper, we present only the interpretation of the whole M2A/b profile, located in the central Tyrrhenian Sea, and of the eastern Tyrrhenian half of the M2A/a (a 548 km long seismic profiles that crosses both the eastern side of the Provençal Basin and the western part of the Tyrrhenian Sea). The original seismic profiles, acquired to 17 s TWT, are available in the "CROP Atlas: seismic reflection profiles of the Italian crust", edited by SCROCCA *et alii* (2003).

The seismic profiles interpretation has been calibrated by analysing and compiling the available data related to the seven ODP Leg 107 wells, sites from 650 to 656 (KASTENS *et alii*, 1988, 1990), and by considering the other available geological and geophysical constraints.

Although several studies of the Tyrrhenian Sea have already pointed out the seismic stratigraphy and the main structural features of this peculiar backarc basin (among the others: FINETTI & MORELLI, 1973; MALINVERNO *et alii*, 1981; FABBRI & CURZI, 1979; FINETTI & DEL BEN, 1986; REHAULT *et alii*, 1987; MASCLE & REHAULT, 1990), the CROP seismic profiles provide new information on the structure and tectonic evolution of the Tyrrhenian Sea. Interpretable seismic signals can be recognised down to 9-10 s TWT or more, well below the usual limit of previously acquired seismic data, sometime making available a seismic image of the Moho discontinuity both in the continental and oceanic domains.

3.1. - CROP M2A/A SEISMIC PROFILE

The interpreted segment of this profile starts north of the Sardinia and, running NW-SE, cuts across the whole continental Sardinia margin (fig. 3).
In its western side, a Mesozoic sedimentary cover has been interpreted between the Upper Messinian reflector and units that can be ascribed to the Varisican basement and to Late-Post Varisican sedimentary and magmatic rocks (outcropping in Sardinia and Corsica). This Mesozoic sedimentary cover, up to about 600 msh TWT thick, is likely made up of Upper Triassic continental clastic deposits and of Jurassic-Lower Cretaceous shallow water carbonates, as suggested by outcrops in the eastern side of Sardinia around the Orosei Gulf.

The eastern margin of the upper slope of the Sardinia margin is characterised by the presence of several N-S trending basement highs. One of them is the Monte Baronie ridge; a slightly asymmetrical horst bounded by faults of both its sides. Within this block we have tentatively interpreted the position of the western front of the Alpine units based on some seismic evidences and as suggested by dredging (COLANTONI *et alii*, 1981).

In the two basins adjacent to Monte Baronie ridge, below the well known strong reflector that characterises the top of the Messinian evaporitic units, a

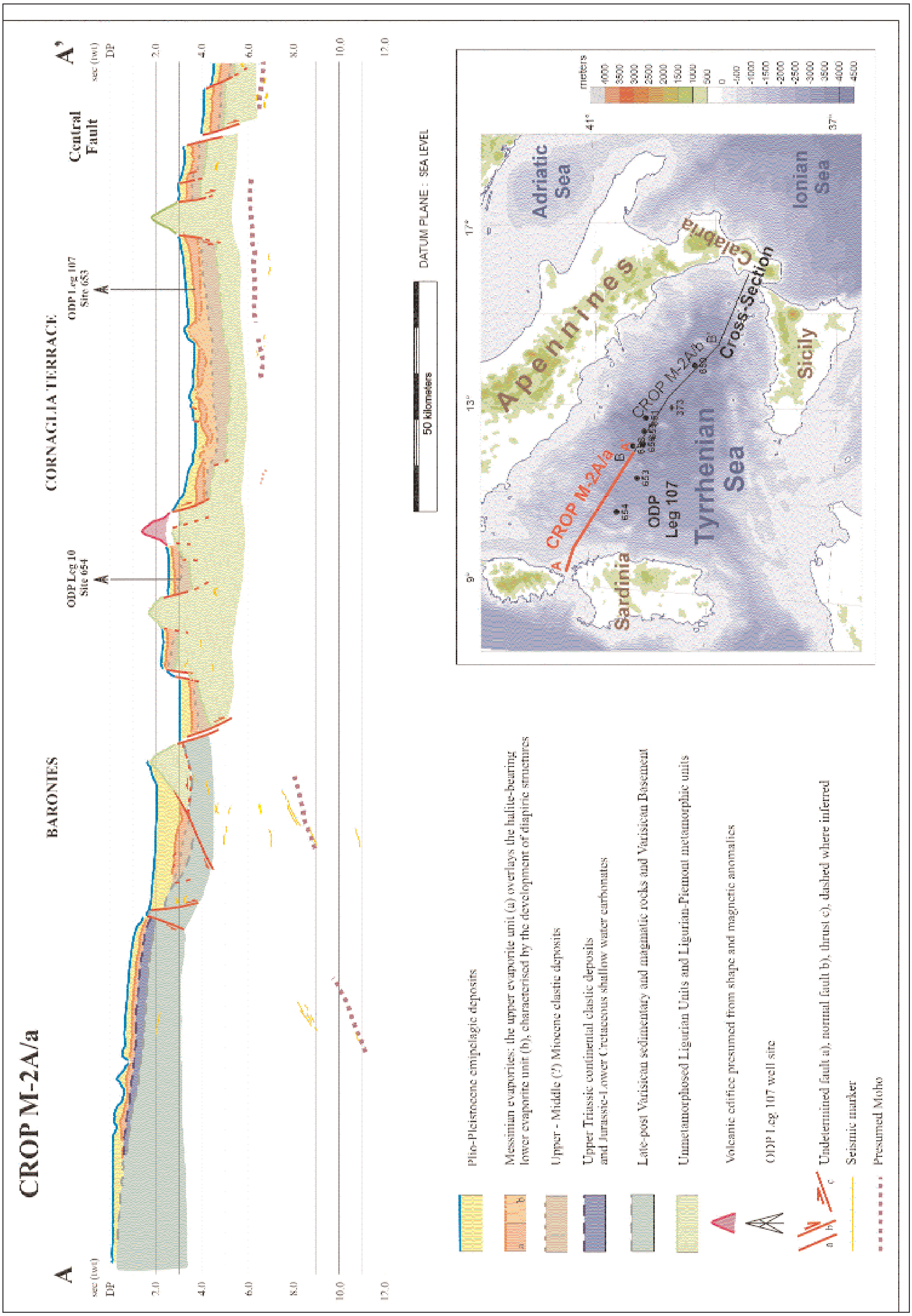

Fig. 3. - *Interpretation of the CROP M2A/a profile.*

large thickness of the "pre-Messinian" sediments can be observed above the acoustic basement. This seismic unit shows quite clear wedge-shaped reflectors arrangement that suggests a syn-rift interpretation.

The onset of the rifting processes on the upper Sardinia slope is a matter of scientific debate. On one side, it is generally accepted (and also well documented) the syn-rift evolution during Upper Tortonian-Messinian times (e.g. MOUSSAT *et alii*, 1986; MASCLE & REHAULT, 1990). On the other side, being the upper Sardinia slope not interested by any ODP drilling, no direct dating is available for these pre-Messinian deposits. As a consequence, a Serravallian-Early Tortonian has been proposed for the rifting process in this area by MALINVERNO *et alii* (1981). In our interpretation, an age older than Upper Tortonian has been considered for the base of these pre-Messinian deposits, taking into account their thickness and in analogy with the correlatable sedimentary cycles on the outcropping Sardinian margin, and the earlier Miocene dating of the rifting to the north (PASCUCCI *et alii*, 1999).

All along the Cornaglia Terrace a strongly reflective horizon is present that represents the top of well-developed Messinian evaporites. According to CURZI *et alii* (1980), an upper evaporite unit overlying a halite-bearing lower evaporite unit have been distinguished (fig. 3); several diapiric structures related to the uplift Messinian salt can be observed.

In the western part of this profile, at about 10-11 s TWT, some strong west-dipping reflectors are recognisable; moving eastward, they became shallower, being at about 8-9 s TWT below Monte Baronie and at 6-7 s TWT in the eastern side of the Cornaglia Terrace. These reflectors have been interpreted as the seismic evidence of the continental Moho and confirm the sharp thinning of the continental crust of the Sardinia margin moving towards the Tyrrhenian basin. Based on our interpretation of these deep reflector on the CROP M2A/a, the crustal thickness decrease might be steeper and slightly shifted westwards than previously imaged (e.g.; RECQ *et alii*, 1984).

3.2. - CROP M2A/B SEISMIC PROFILE

This profile represents the south-eastwards prosecution of the CROP M2A/a (with a 30 km overlap). It intersects the "Central Fault", and runs through the Vavilov Basin, the Issel swell, and the western portion of the Marsili Basin. The interpretation of this profile (fig. 4) offers some further information on the deeper part of the Tyrrhenian Sea.

East of the "Central Fault", there are no evidences of the typical Messinian acoustic facies and, as documented by sites 652 and 656, the Messinian deposits show a sub-aerial and lacustrine facies (KASTENS *et alii*, 1988, 1990).

Further to the southeast, a sharp transition between the stretched continental domain and the oceanic one can be inferred. The top of the acoustic basement, interpreted as the top of the oceanic crust, has been represented; no differentiation has been possible between the serpentinized peridotite and the lava flows and basaltic breccias drilled by the site 651.

The Issel swell shows a faulted acoustic basement made up, according to dredging (COLANTONI *et alii*, 1981; BIGI *et alii*, 1992), of shallow and deep water carbonates, siliciclastic rocks and low- to medium-grade metamorphites; the first one may be Mesozoic while the other are of undefined age.

Moving south-eastwards, a picture of the general structure of the western side of the Marsili Basin, the younger of the basins floored by oceanic crust, is provided.

Although some multiples partially confuse the seismic image, it is worth noting that some scattered deep reflectors, tentatively attributed to the Moho, can be observed also on this profile. In particular, some strong reflectors are recognisable below the eastern margin of the Issel swell; if correctly interpreted, they might show a Moho significantly shallower than usually described (e.g. NICOLICH, 2001).

4. - EXTENSION IN THE TYRRHENIAN SEA

Along the section MS1 of FINETTI & DEL BEN (1986) there are about 162 normal or transtensional faults. The average spacing of the faults is about 4 km, but it raises to about 16-17 when only the most relevant are computed (fig. 5). The extension measured on the faults is around 67 km. Moreover there are 186 km of oceanic crust summing the Vavilov and Marsili interpreted sub-basins. Then the conservative amount of extension measured in the central-southern Tyrrhenian basin in the seismic section MS1 is about 253 km (67+186), along a section 640 km long (fig. 5). This value does not consider the stretching of the pre-existing alpine thickening and it is computed adding the horizontal component of the normal faults plus the oceanic segments. In the northern Tyrrhenian basin and Tuscany, where no oceanic crust crops out, a much smaller extension of about 25 km has been calculated from Corsica to Tuscany, again disregarding Alpine thrusting (fig. 6).

In order to have the entire extension in the backarc basin, these values have to be added to the horizontal stretching of the Provençal basin and of the normal faults in the related conjugate continental margins. It is maintained that moving northward, the extension decreases, like shortening does in the Apennines accretionary prism (BALLY *et alii*, 1986).

Therefore, computing the extension in the Provençal basin to about 300 km, the total stretching in the maximum extended backarc amounts to > 553 km. The variability of the extension in the Tyrrhenian sea is accommodated by frequent transfer zones with different orientation, oblique or normal to the grabens and horts.

Extension in the hangingwall of the Apennines can be differentiated in three different settings: 1) Extension in the Tyrrheanian sea and related conjugate margins, where subsidence is prevailing, and related to

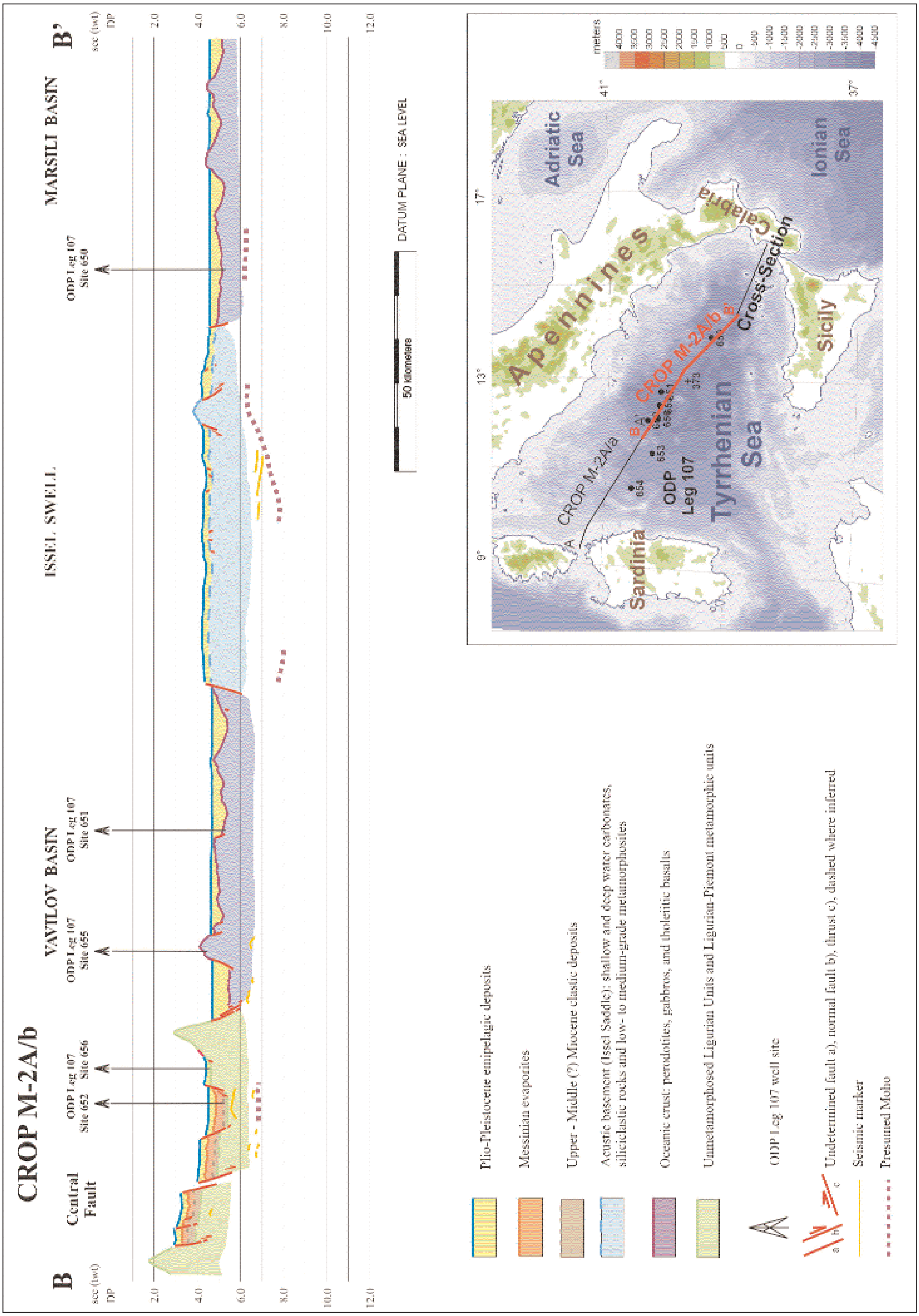

Fig. 4. - *Interpretation of the CROP M2A/b profile.*

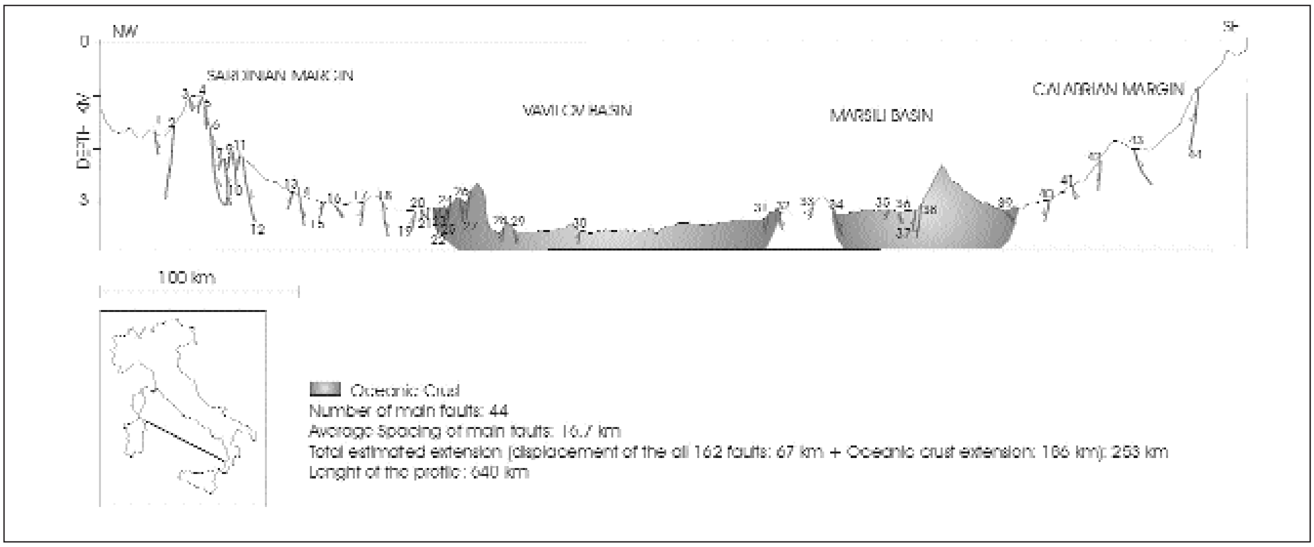

Fig. 5. - *Cross-section of the central-southern Tyrrhenian basin, with location of the main faults and the area where oceanic basement has been inferred. Base profile after* FINETTI & DEL BEN (1986).

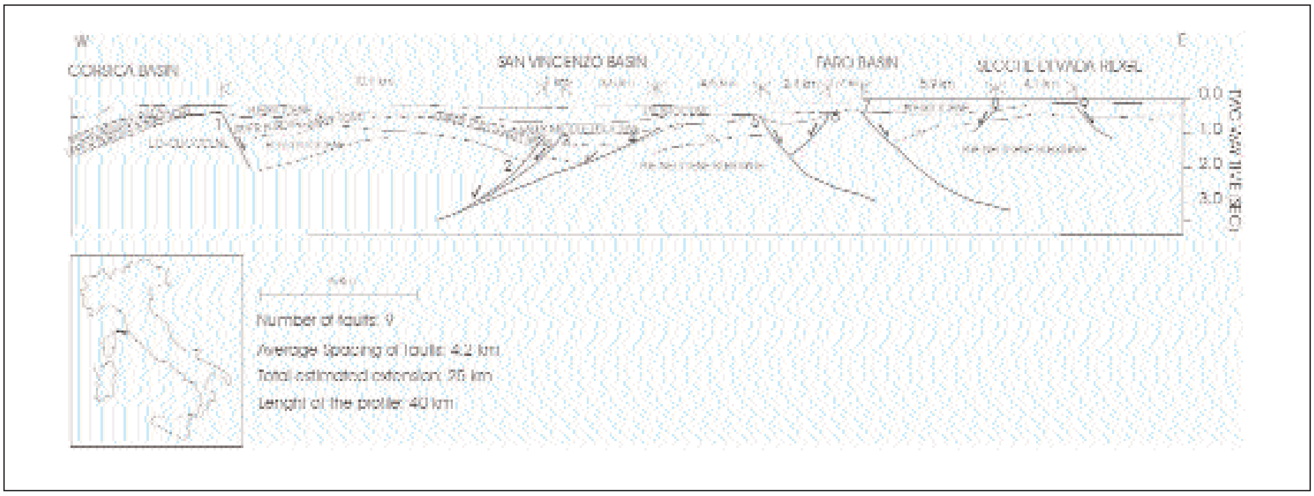

Fig. 6. - *The extension in the northern Tyrrhenian is about 10 km, and it raises to at least 25 km when including Tuscany, disregarding pre-extension thickening related to the Alpine orogen. Fault spacing is also shorter than in the southern Tyrrhenian. Cross-section after* PASCUCCI *et alii* (1999).

leghtening between the backarc margins. 2) Extension along the axis of the Apennines, where uplift is prevailing, with master faults mainly dipping toward the orogen foreland, (i.e., “E”-ward) and associated to the space generated by the slab retreat; this rifting is located in the uplifting area of the belt probably because accretion at the front of the orogen is larger than volume loss for slab rollback. 3) Extension perpendicular to the Apennines, related to the leghtening of the arc (DOGLIONI, 1991). In fig. 7 is proposed the kinematic setting of the Apennines subduction where extension in the hangingwall is generated both by space compensation in the subduction hinge (e.g., along the uplifting Apennines), and the increasing distance between the belt and the conjugate margin of the backarc basin (e.g., in the Tyrrheanian Sea).

In the Apennines, extension generated by hinge rollback is located in an area of regional uplift. This contradictory behaviour could be explained by the competing loss of volume generated by the slab rollback, and the volume added to the accretionary prism and/or by the Tyrrhenian asthenospheric mantle wedging. The uplift in the Apennines appears located where at depth there is the wedge of the active prism, and its thickening should contribute to the uplift. In the meanwhile, the slab retreat is responsible for the loss of volume in the hangingwall of the subduction. Therefore if the accretion is compensating part, but not all of the volume loss, extension might occur.

5. - EASTWARD MANTLE FLOW

Eastward mantle flow in the western Mediterranean is kinematically required by the slab rollback of the Apennines subduction (fig. 8): the

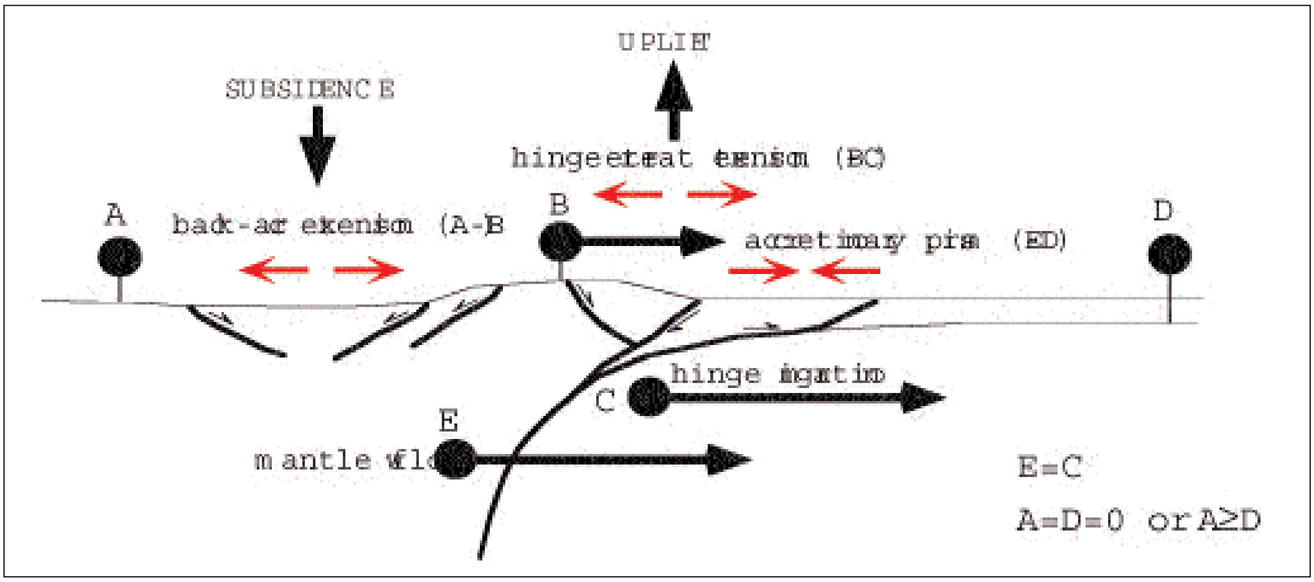

Fig. 7. - *Kinematic model of a west-directed subduction where two extensional settings form between A and B in the area of generalized subsidence (e.g., Tyrrhenian basin), and between B and C, along the uplifting belt (e.g., Apennines). The subduction hinge (C) eastward migration is faster than the convergence rate between D and B. Since C is faster than B, extension occurs also along the belt axis.*

volume left by the slab retreat is in fact necessarily filled by the upper mantle, regardless this mantle flow is the cause or a consequence of the slab rollback. The same kinematics are required for the mantle to the east of the slab: in order to allow the eastward slab retreat, mantle has to move eastward. Independently from this consideration, the relative eastward mantle flow is predicted by the westward drift of the lithosphere (Doglioni *et alii*, 1999) detected at the global scale in the hotspot reference frame which has been computed in an average of about 4.9 cm/yr (Gripp & Gordon, 2002). The slab retreat in the Mediterranean has generally been ascribed to the negative buoyancy of the slab, i.e., the slab pull (Royden, 1993; Faccenna *et alii*, 2003). However, apart other general issues, this mechanism fails to explain a number of observations such as the along slab compression in the southern Tyrrhenian (Frepoli *et alii*, 1996), and the subduction of continental lithosphere along the central-northern Apennines.

The eastward mantle flow in the western Mediterranean appears supported by the asymmetry indicated by the polarization of the seismic waves (Margheriti *et alii*, 1996) due to the elongation of olivine crystals in the mantle. The anisotropy deviates to an Apenninic trend underneath the belt: these data might be an indication of a flow underneath the Tyrrhenian backarc where the crystals should parallel the direction of mantle movement, and the encroachment with the subduction zone underneath the Apennines where the crystals should reorient due to the obstacle of the subduction.

The eastward mantle flow can account for the progressive eastward rejuvenation and boudinage of the western Mediterranean basins, e.g., from the Provençal to the Tyrrhenian, with the Vavilov, Marsili and Paola sub-basins (Gueguen *et alii*, 1997). The boudins and necks are also asymmetric: the base of the crust and of the lithosphere are in fact shifted several tens of km eastward relative to the topography of the basins and swells (Cella *et alii*, 1998), coherently with a shear between lithosphere and underlying mantle (fig. 9).

6. - ON THE CORSICA-SARDINIA UPLIFT

The micro-continental plate of Corsica and Sardinia uplifted about 2 km as a single block together with the Alpine Corsica thrust sheets during the late Early Miocene (Cavazza *et alii*, 2001), and there is not a unique explanation of this phenomenon. It appears to be an uniform upward movement related to isostatic rebound. We discuss here the hypothesis that it is related to the opening of the Provençal basin to the west. Oceanization in the Provençal Basin (Rollet *et alii*, 2002) occurred between 19-15 Ma, but the rift started during the Late Oligocene (e.g., Gueguen *et alii*, 1997).

The mantle uprise along rift zones determines partial melting and a residual lighter mantle (Oxburgh & Parmentier, 1977) with lower density of 20-60 kg m^{-3}, than the undepleted mantle. The residual mantle, less dense and containing some fluids, when displaced to the east, should generate a mass deficit with respect to the western limb of the ridge, where this low-density mantle did not propagate. Moving relatively eastward, the depleted mantle, determines asymmetry along oceanic rifts and eventually the uplift of the continent to the east as Africa (Doglioni *et alii*, 2003). This model could be applied to the opening of the Provençal basin and the later uplift of the adjacent Corsica-Sardinia continental lithosphere situated to

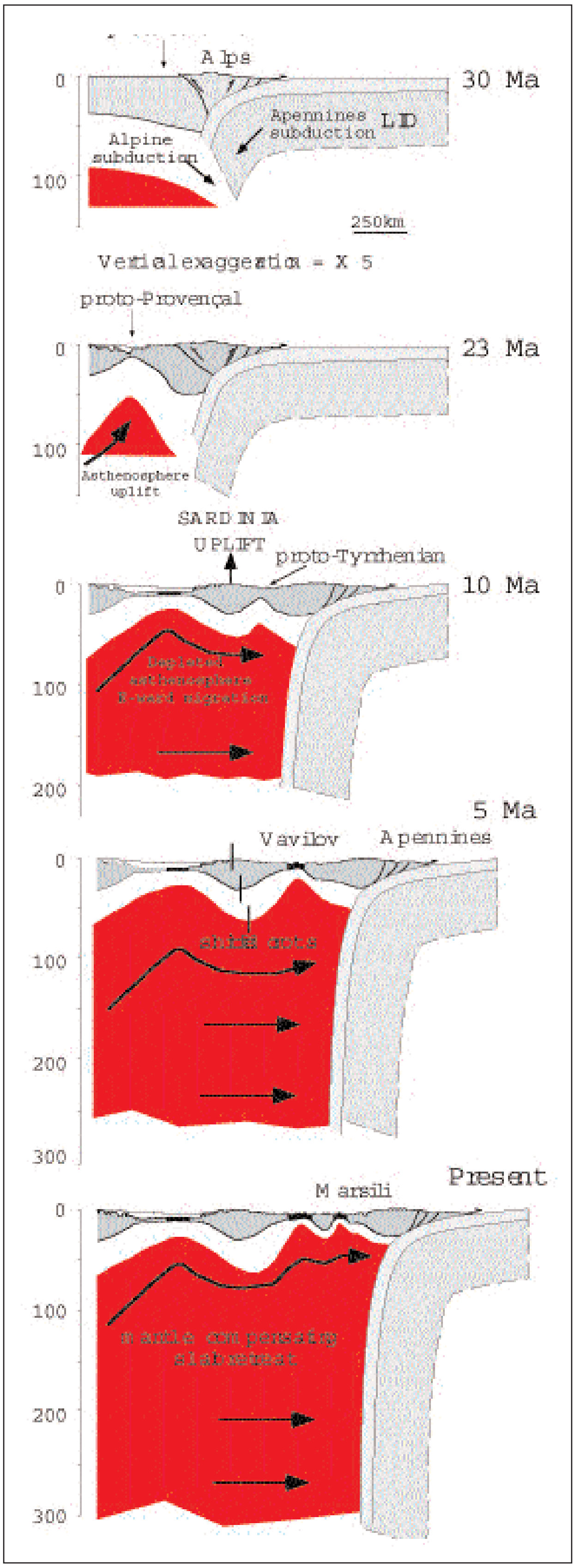

Fig. 8. - *Slab retreat and boudinage of the backarc basin in the hangingwall of the Apennines subduction during the last 30 Ma are interpreted in the central western Mediterranean (modified after* GUEGUEN *et alii*, 1998*). Slab retreat implies mantle compensation, in other words "eastward" mantle flow.*

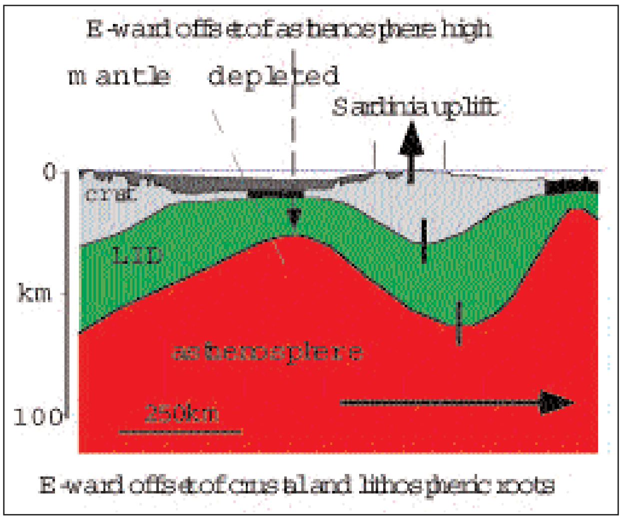

Fig. 9. - *Asthenosphere uplift and depletion associated to the Provençal basin opening (Late Oligocene-Early Miocene) determined a lighter mantle. An eastward mantle flow is inferred for the rollback of the steep Apennines slab, the shear wave splitting, and the westward drift of the lithosphere. The eastward mantle shear could explain the asymmetry of the Sardinia roots (data after* CELLA *et alii*, 1998*) and the Miocene uplift of Corsica-Sardinia due to an isostatic rebound related to the underlying transit of a less dense asthenosphere.*

the east: the substitution of undepleted mantle with depleted lighter mantle underneath Corsica-Sardinia could explain their generalized uplift (fig. 9). A similar model could be invoked for the uplift of the Balearic promontory, due to the opening of the Valencia trough to the west.

7. - SOUTH TYRRHENIAN MAGMATISM

The South Tyrrhenian Area (STA) is located south of 41°N and is bordered in the east by Campania and Calabria, in the west by Sardinia and in the south by Sicily. This domain is characterized by a widespread and very complex magmatism, with different petrogenetic affinities (figures 10 & 11). One common petrogenetic feature of this magmatism is that its ultimate source seems to be the mantle; anatectic magmas derived from the partial melting of continental crust are in fact typically absent in this area, in contrast to the northern Tyrrhenian region where they are conspicuous by their presence (SERRI *et alii*, 2001).

In order to minimize the effects of crustal contamination and shallow fractionation, and considering the petrological and geochemical data for the most primitive products only, we observe some important geochemical heterogeneities in the mantle of the southern Tyrrhenian domain. If we classify the volcanic products according to the geochemical characteristics of the mantle from which they have originated, then three main sources emerge.

Subduction-related source(s), which gave origin to two main suites: the south Tyrrhenian orogenic association (STOA), and the K-rich alkaline association of the

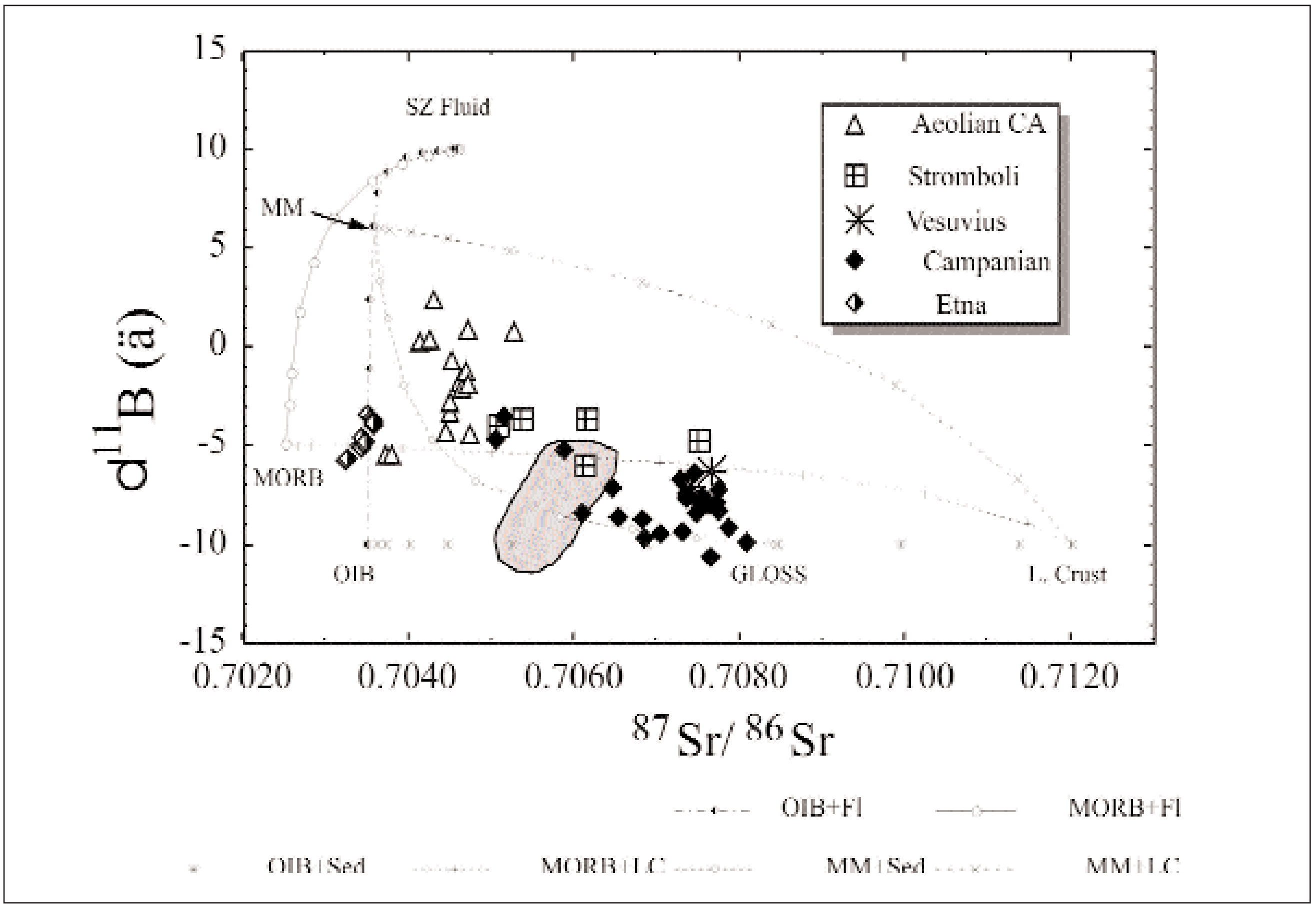

Fig. 10. - *δ^{11}B vs. 87Sr/86Sr diagram for South Tyrrhenian Quaternary volcanic rocks* {δ^{11}B=*[(11$_B$/10$_B$)sample/(11$_B$/10$_B$)Std-1]*1000*}. *Dashed lines represent mixing trajectories between different hypothetical end-members (L.C., lower crust, SZ fluid, subduction-related fluid; MM, OIB-type mantle modified by subduction-related fluids;* GLOSS, (PLANK & LANGMUIR, 1998). G*ray area encircles Mt. Vulture samples. (from ,* TONARINI*, unpubl. Data).*

Central Campanian Province (CCP). The STOA includes the active volcanic arc of Aeolian Islands, made up of seven islands and several seamounts that extend east and west of the emerged arc. The erupted products form a suite with a variable affinity from tholeiitic to shoshonitic through calc-alkaline and high-K calc-alkaline rocks; K-rich alkaline products are also present and characterize the most recent volcanics of Stromboli and Vulcano (eastern sector of the arc). Several seamounts older than the Quaternary Aeolian volcanics and made up of rocks with an evident calc-alkaline affinity have been described in back-arc positions [e.g. Anchise, Sisifo, Marsili, Palinuro, Vavilov Basin (ARGNANI & SAVELLI, 1999; MARANI & TRUA, 2002; TRUA *et alii*, 2002). They are considered as isolated, partially dismembered portions of the oldest arc structures, abandoned as a consequence of the trenchward SE migration of the arc induced by the roll-back of the subducting Ionian slab (MALINVERNO, 1986). The morphotectonic features of the STOA and, in particular, the absence of high-standing cross-arc ridges (MARANI & TRUA, 2002) suggest a high rate of back-arc extension: in these conditions magma production was unable to keep pace with the widening of the back-arc (WRIGHT, 1996).

Evidence of the oldest Tertiary arc related to the westward-oriented subduction still remains in Sardinia, where an orogenic sequence ranging from 32 to 13 Ma is exposed along the western part of the island. The volcanic products show an affinity varying from tholeiite (southernmost sector) to calc-alkaline (northern part, DOWNES *et alii*, 2001; BROTZU, 1997) noteworthy is the eruption during the more extensional phases of the construction of the arc of primitive magmas, such as high-Mg basalts (MORRA *et alii*, 1997; MATTIOLI *et alii*, 2000).

The CCP includes the volcanic centres of the Campi Flegrei, Ischia-Procida and Somma-Vesuvio. The erupted products consist of slightly undersaturated or saturated K-alkaline rocks and ultra-alkaline leucite-bearing undersaturated products. Evolved terms are dominant in Ischia and the Campi Flegrei where significant contamination processes by crustal material in shallow magma chambers have been documented (PAPPALARDO *et alii*, 2002). The geochemical features of the primitive rocks exhibit a subduction-related signature, as indicated by high LILE/HFSE ratios and the negative anomalies of Ta, Nb, Ti and, to a lesser extent, Hf in the trace element profiles, normalized to primordial mantle (fig. 11, CONTICELLI *et alii*, 2002).

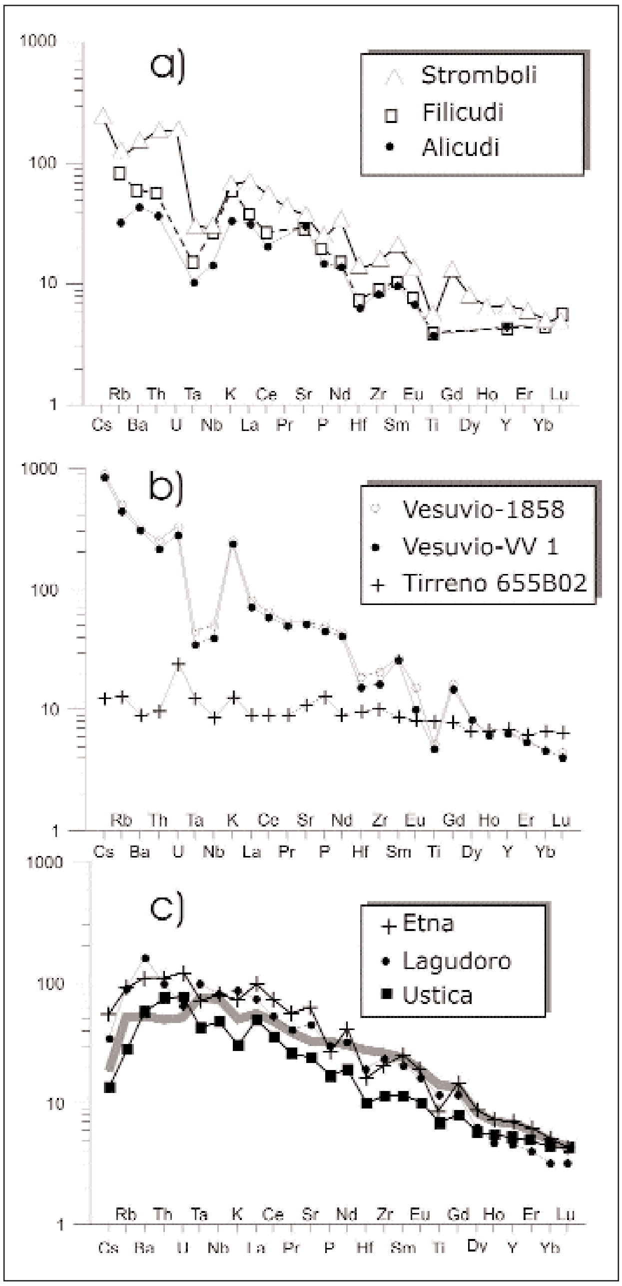

Fig. 11. - *Primordial mantle normalized multi-element patterns for Quaternary selected samples from South Tyrrhenian Area* (METRICH *et alii,* 2001*). Normalizing values are from* (MCDONOUGH & SUN, 1995). *Stromboli: scoria STR 43 (Mg#=61.2)* (METRICH *et alii*, 2001)*; Filicudi: La Canna, STR 197 (Mg#=63.9)* (FRANCALANCI & SANTO, 1993)*; Alicudi, STR185 (Mg# 62.8)* (FRANCALANCI *et alii,* 1993). *Vesuvio: 1868 phonotephrite lava (Mg#55); VV1, S. Maria La Bruna historic phonotephrite lava (Mg#=59.3) (M. D'Orazio unpubl. data); Tyrrhenian Basin,ODP site 655 B02* (BECCALUVA *et alii*, 1990) (GASPERINI *et alii*, 2002). *Etna: 1998 South-East Crater lava (Mg#53.9) (M. D'Orazio unpubl. data); Lagudoro lava (Mg# 65.9)* (GASPERINI *et alii,* 2000)*; Ustica: submarine olivin basalt (Mg#61.4) (M. D'Orazio unpubl. data).*

MORB-type source, which produced the basalts that form the floor of the Vavilov (Late Miocene) and Marsili (Late Pliocene-Early Pleistocene) basins (SERRI *et alii*, 2001), which evolved from the back-arc widening of the hangingwall plate induced by the roll-back of the ongoing subduction of the Ionian plate.

OIB-like sources, (fig. 11) which generated scattered basaltic covers or volcanic complexes in Sardinia and on its eastern off-shore margin (Late Miocene-Pleistocene), some seamounts in the central and south Tyrrhenian basin (e.g. Vavilov, Magnaghi and Aceste), the island of Ustica and the related Prometeo Ridge, and the Etna Volcano (ARGNANI & SAVELLI, 1999; LUSTRINO *et alii*, 2000; SCROCCA *et alii*, 2003).

The tectonic setting of this volcanism shows contrasting features; for example, Sardinian volcanism and the Tyrrhenian seamounts lie within the European continental hinterland or the thinned Tyrrhenian basin, relatively far from the active volcanic arc, whereas Ustica is located on the eastern extension of the active Aeolian volcanic arc, between the calc-alkaline seamounts Sisifo and Enarete to the east and Anchise to the west; finally, Mount Etna is in a peculiar position, in the foreland of the Apennine accretionary wedge (ARGNANI & SAVELLI, 1999; GASPERINI *et alii*, 2001; DOGLIONI *et alii*, 2001).

The distribution and first-order geochemical characteristics of the STA volcanics highlight two main features, the first of which is the predominance of products with a clear orogenic geochemical signature. The composition of the emitted lavas is extremely variable, however, ranging from rocks compositionally akin to the lavas forming the magmatic arcs at destructive margins (Aeolian arc) to K-rich silica, strongly undersaturated and saturated rocks (PC rocks). The other major feature is the occurrence of rocks closely associated with the orogenic suites that have an intraplate or OIB geochemical hallmark.

It is commonly accepted that, in convergent zones, orogenic magmas are generated by a melting in-wedge mantle modified by metasomatizing components (aqueous fluids or silicate melts) derived from a subducting slab (TATSUMI & EGGINS, 1995). Geochemical and isotopic data obtained from STA primitive rocks can be used to constrain the nature of the mantle sources; of particular importance for our comprehension of their geochemical features is the distribution of the incompatible fluid mobile elements, especially B and its isotopic ratio. Boron is, in fact, a strongly incompatible element, like Th and Nb; however, as it shows a marked affinity for the fluid phase, its behaviour is decoupled from that of incompatible immobile trace elements such as Nb, when a fluid phase is present (BRENNAN *et alii*, 1996; LEEMAN, 1996). Furthermore, there are distinct reservoirs of boron: in fact B is relatively enriched in altered oceanic crust (AOC) and pelagic sediments, whereas it is strongly depleted in the upper mantle and lower continental crust (LEEMAN, 1996). The B-isotope composition can further help to constrain the geochemical features of the sources providing components that may modify upper mantle composition. AOC and subduction-related fluids are, for example, characterized by markedly positive $\delta^{11}B$ values, whereas negative values are found in the upper mantle, continental crust and sediments (RYAN *et alii*, 1995; ISHIKAWA & TERA, 1997).

The efficacy of B in differentiating source components can be strongly enhanced if its isotopic composition is combined with other isotopic ratios (e.g. Sr and Nd) and/or with mobile/immobile incompatible trace element ratios, such as B/Nb. This is shown in fig. 10, where the B isotope ratio is plotted against $87_{Sr}/86_{Sr}$ ratio for the Quaternary volcanic rocks related to the Apen nine subduction. The diagram shows the poles of the main end members contributing to a definition of the upper mantle sources. The plotted data clearly show the distinction between the volcanics of the Aeolian Islands and Campanian Province (TONARINI *et alii*, 2001a; 2004). In fact, the trends defined by the analyzed products of the two associations intersect, suggesting that the dominant component metasomatizing the mantle source in the Aeolian products is represented by fluids related with altered oceanic crust, whereas the Campanian products seem to be related with a source whose geochemical characteristics have been affected by a component of sedimentary origin, along with a subduction-related fluid with an AOC signature. Figure 10 also reports the curves of a binary mixing between the assumed end members to give a semi-quantitative indication of the interacting components. The data can also be used to acquire information on the pristine nature of the mantle before it was affected by metasomatic processes. Although B-isotopes are not particularly adept at discriminating mantle sources (CHAUSSIDON & MARTY, 1995; RYAN *et alii*, 1996), the combined geochemical data of fig. 10 as well as the values of mobile/immobile incompatible element ratios (TONARINI *et alii*, 2004) appear consistent with a model involving a depleted MORB-like mantle for the Aeolian magmas, whereas a more enriched OIB-like mantle source is required for the Campanian rocks; an attenuated OIB-signature for the CP volcanics has also been assumed, on the basis of the incompatible trace element distribution and isotopic data on the most primitive rocks (BECCALUVA *et alii*, 1991; GASPERINI *et alii*, 2002).

8. - GEODYNAMIC INTERPRETATION

The subduction-related Quaternary volcanism of the south Tyrrhenian Basin is characterized by remarkable geochemical and petrological variations that develop along the magmatic arc; they have been attributed to the interaction of mantle wedge with a predominant component linked to AOC in the Aeolian magmas or to sediments in the CP magmatism.

The geological and seismological data indicate that, at least since the Miocene, the Adriatic plate has been subducting westwards beneath the Apenninic arc, NW in the Calabrian arc and N in Sicily (DOGLIONI *et alii*, 1998; AMATO & CIMINI, 2001). The subducting plate shows important lateral variations, appearing oceanic in the Calabrian-Ionian sector, and continental under the Campanian region or in Sicily (CATALANO *et alii*, 2001; CARMINATI *et alii*, 2002). These lateral structural and compositional variations account for the differences in seismicity between the Apennine and Calabrian arcs: underneath the Apennines the earthquake foci have been monitored to a depth of about 90 km, whereas the Calabrian arc is characterized by a well-defined Benioff zone extending for 500 km (AMATO *et alii*, 1997); the differential retreat of the subduction hinge between Puglia, Calabria and Sicily is also considered a consequence of the lateral changes in composition of the subducting slab (DOGLIONI *et alii*, 2001). This geodynamic scenario explains the geochemical features of the main components metasomatizing the mantle sources of the South Tyrrhenian arc magmatism and, in particular, of the AOC-related component in the Aeolian arc and the sedimentary or crustal component in the Campanian magmas. Thus, the geochemical variations observed in erupted products from the Aeolian Islands to the Campanian Province probably reflect the changes in lithosphere from oceanic to continental.

The occurrence of magma with an OIB signature in the general convergence context of the south Tyrrhenian region is a more intriguing question. The existence of intraplate magmatism in a back-arc situation, i.e. Sardinian and Tyrrhenian volcanism, can be explained by mantle decompression melting, triggered both by its movement into the space created by the rollback of the subducting plate and the rifting process that eventually led to the opening of the Tyrrhenian Basin. The isotope characteristics of the erupted products seem to indicate the presence of an EM-1 reservoir linked with ancient oceanic plateau material recycled through a mantle plume (GASPERINI *et alii*, 2001); however, there is no geological and volcanological evidence of a Plio-Quaternary plume in northern Sardinia (e.g. very low eruption rate and absence of regional upwarping).

It is more difficult to explain the presence of the magma with predominant intraplate features along or close to the magmatic arc, such as Ustica and Etna. Geochemical and isotope variations have been detected at Mt. Etna, despite the relatively homogeneous petrological nature of its erupted products. In particular, the good correlation between $\delta^{11}B$ and $87_{Sr}/86_{Sr}$ and the fluid mobile elements (TONARINI *et alii*, 2001b; see also fig. 10), has been interpreted as the result of contamination by subduction-related fluids released by the subducted Ionian slab of the sub-slab mantle (asthenosphere). The relatively deep mantle was able to raise because a major structural discontinuity, considered a vertical slab window, opened in the subducting plate at the transition between the oceanic Ionian and continental Sicilian lithospheres. This geodynamic model can be tentatively extended all along the Apennines subduction zone where a drastic structural change occurs in the nature of the slab, leading to a differential retreating rate of the subduction hinge and, therefore, to the creation of a vertical window. This phenomenon could be applied to the plateau volcanism of Ustica and Prometeo, on the northern prolongation of the Malta escarpment. Another structural situation of slab discontinuity is expected at the conjugate location with respect to the Etna and Malta escarpment.

Magmatism is likely triggered by fluids released by slabs at around 150-250 km depth. Magmatism is sensitive to composition of the downgoing slab, thermal state of the slab and surrounding mantle, dip of the slab, velocity of the subduction, fluids content of the slab, and possibly the thickness and composition of the hangingwall plate and mantle. In the hangingwall of the Apennines subduction, as an example, there is volcanism fed by subducting both continental and oceanic lithospheres. As a hypothesis, since continental crust melts at lower temperatures than oceanic crust, shallower depth for magma generation is expected for continental crust with respect to oceanic crust; this could explain the closer location of the continental-related volcanism to the subduction hinge in the central-northern Apennines subduction zone with respect to the southern Tyrrhenian Eolian arc (fig. 12).
The Tyrrhenian Sea appears as the area where the asthenosphere and the underlying upper mantle replaced the volumes of the heterogeneous foreland lithosphere that were consumed by the Apennines subduction.

Acknowledgments

Many thanks to Michael Marani *for inviting us to contribute to the volume.* Sonia Tonarini *and* Massimo D'Orazio *are thanked for useful discussions and for providing unpublished isotopic data. Research supported by* Cofin 2001, ASI 2002 and Ateneo La Sapienza 2003.

REFERENCES

Amato A., Alessandrini B., Cimini G., Frepoli A. & Selvaggi G. (1993) – *Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity.* Ann. Geofis., **36** (2): 201-214.

Amato A., Chiarabba C. & Selvaggi G. (1997) - *Crustal and deep seismicity in Italy (30 years after).* Ann. Geofis., **40**: 981– 993.

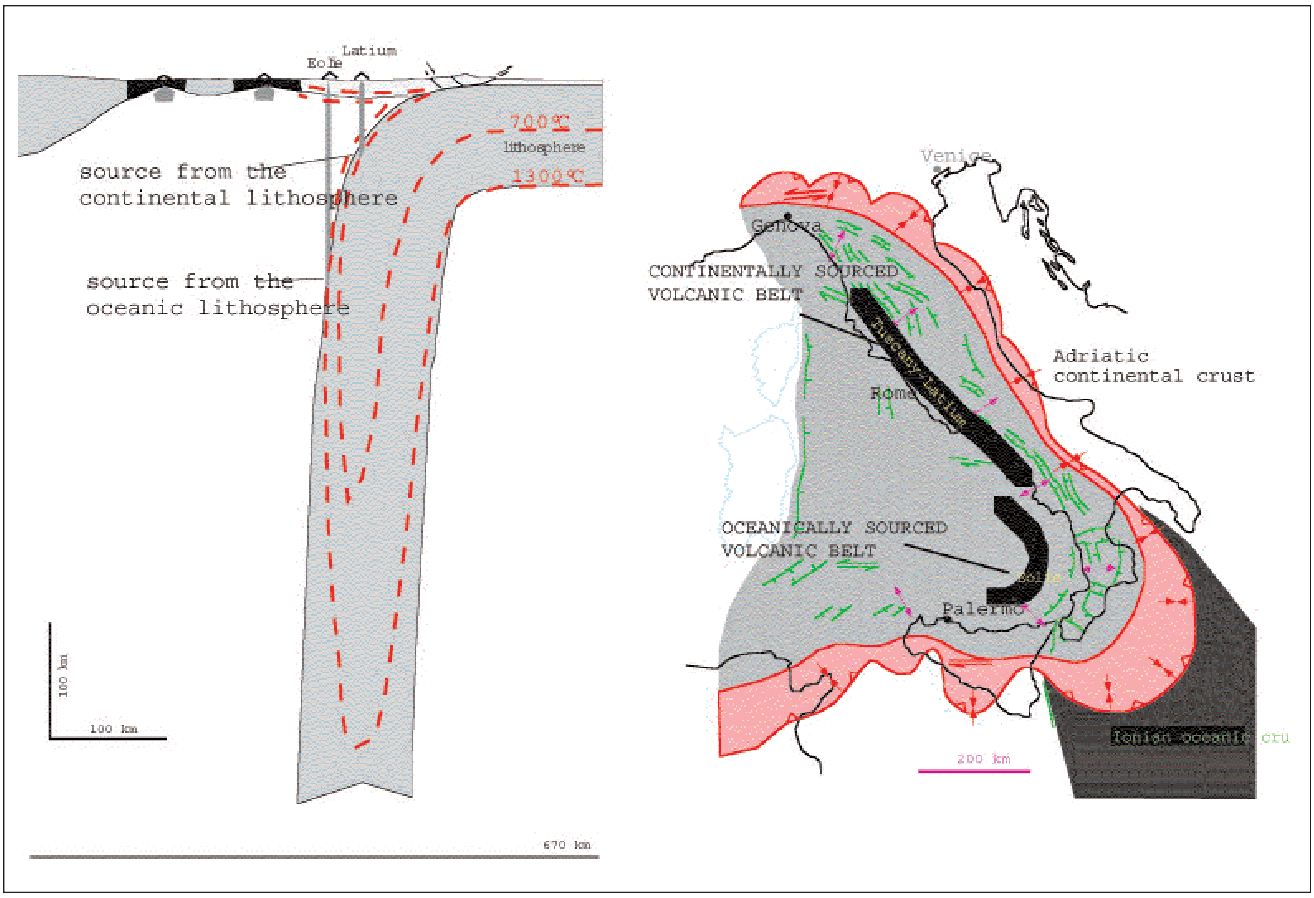

Fig. 12. - *The depth of fluids release and of melt generation along a subduction zone is a function of the composition of the downgoing rocks. Continental crust melts at lower temperature (650-800°C) than oceanic crust (1200-1300°C). As an application, the Apennines have both continental (Adriatic) and oceanic (Ionian) lithosphere subducting toward the west underneath the belt. The related magmatism is likely shallower for the continental subduction than the oceanic one because melting temperature is reached earlier. This could explain the shorter distance to the subduction hinge and the inland location of the subduction-related magmatism in the central-northern Apennines with respect to the Eolian volcanic arc in the southern Tyrrhenian.*

AMATO A. & CIMINI G.B. (2001) - *Deep structure from seismic tomography.* In: VAI G.B. & MARTINI I.P. (Eds.): "*Anatomy of an Orogen: the Apennines and Adjacent mediterranean basins".* Kluwer Academic Publishers, Dordrecht, The Netherlands, 33-45.

AMATO A., CIMINI C., ALESSANDRINI B. (1991) - *Struttura del sistema litosfera–astenosfera nell'Appennino Settentrionale da dati di tomografia sismica.* Studi Geologici Camerti, Vol. Spec. (1991/1): 83–90.

ARGNANI A. & SAVELLI C. (1999) - *Cenozoic volcanism and tectonics in the southern Tyrrhenian sea: space-time distribution and geodynamic significance.* J. Geodynamics, **27:** 398-321.

BALLY A.W., BURBI L., COOPER C. & GHELARDONI R. (1986) - *Balanced sections and seismic reflection profiles across the central Apennine.* Mem. Soc. Geol. It., **35**: 257-310.

BECCALUVA L., BONATTI E., DUPUY C., FERRARA G., INNOCENTI F., LUCCHINI F., MACERA P., PETRINI R., ROSSI P.L., SERRI G., SEYLER M., SIENA F. (1990) - *Geochemistry and mineralogy of volcanic rocks from ODP sites 650, 651, 655, and 654 in the Tyrrhenian Sea.* In: STEWART: N.J. (Ed.): "*Procedings of the Ocean Drilling Program, Scientific Results".* U.S. Gov. Print. Off., Washington, D.C., 107, pp. 49-74.

BECCALUVA L., DI GIROLAMO P. & SERRI G. 1991. *Petrogenesis and tectonic setting of the Roman volcanic Province, Italy.* Lithos, **26**: 191-221.

BIGI G., CASTELLARIN A., CATALANO R., COLI M., COSENTINO D., DAL PIAZ G.V., LENTINI F., PAROTTO M., PATACCA E., PRATURLON A., SALVINI F., SARTORI R., SCANDONE P. & VAI G.B. (1989) - *Synthetic structural-kinematic map of Italy, scale 1:2.000.000.* CNR, Progetto Finalizzato Geodinamica, Roma.

BIGI G., COSENTINO D., PAROTTO M., SARTORI R. & SCANDONE P. (1992) - *Structural Model of Italy. Scale 1:500.000.* Quaderni de "La Ricerca Scientifica", 114, Vol. 3. CNR.

BRENNAN J.M., NERODA E., LUNDSTROM C.C., SHAW H.F., RYERSON F.J. & PHINNEY D.L. (1998) - *Behaviour of boron, beryllium, and lithium during melting and crystallization: Constraints from mineral-melts partitioning experiments.* Geochim. Cosmochim. Acta, **62**: 2129-2141.

BROTZU P. (1997) - *The calcalkaline volcanism in Sardinia.* Per. Mineral., **66**: 1-231.

CALCAGNILE G. & PANZA G.F. (1981) – *The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions.* Pure Appl. Geophys., **119**: 865-879.

CAPUTO M., PANZA G. F. & POSTPISCHL D. (1970) – *Deep structure of the Mediterranean Basin.* J. Geophys. Res., **75**: 4,919-4,923.

CARMINATI E., GIARDINA F. & DOGLIONI C. (2002) - *Rheological control of subcrustal seismicity in the Apennines subduction (Italy).* Geophys. Res. Lett., **29**, doi:10.1029/2001GL014084.

CATALANO R., DOGLIONI C. & MERLINI S. (2001): On the Mesozoic Ionian basin. Geophys. J. Int., **144**: 49-64.

CAVAZZA W., ZATTIN M., VENTURA B. & ZUFFA G.G. (2001) - *Apatite fission-track analysis of Neogene exhumation in northern Corsica (France)* Terra Nova, **13**: 51-57.

CELLA F., FEDI F., FLORIO G. & RAPOLLA A. (1998) - *Optimal gravity modelling of the litho-asthenosphere system in Central Mediterranean.* Tectonophysics, **287**: 1-4, 117-138.

CHAUSSIDON M. & MARTY B. (1995) - *Primitive Boron Isotope Composition of the Mantle.* Science, **269** (121): 383-386.

CIMINI G.B. (1999) – *P-wave deep velocity structure of the southern Tyrrhenian subduction zone from non-linear teleseismic travel time tomography.* Geoph. Res. Let., **26** (24): 3709-3712.

COLANTONI P; FABBRI A; GALLIGNANI P., 1981. *Seismic-stratigraphic interpretation of high resolution profiles; some applied examples.* Boll. Geof. Teor. Appl., **23**, 90-91, 89-106.

CONTICELLI S., D'ANTONIO M., PINARELLI L. & CIVETTA L. (2002) - *Source contamination and mantle heterogeneity in the genesis of Italian potassic and ultrapotassic volcanic rocks: Sr-Nd-Pb isotope data from Roman Province and Southern Tuscany.* Mineral. and Petrol., **74**: 189-222.

CURZI P; FABBRI A; NANNI T., 1980. The Messinian evaporitic event in the Sardinia Basin area (Tyrrhenian Sea). Mar. Geol., **34**, 3-4, 157-170.

DE GORI P., CIMINI G.B., CHIARABBA C., DE NATALE G., TROISE C. & DESCHAMPS A. (2001) - *Teleseismic tomography of the Campanian volcanic area and surrounding Apenninic belt.* J. Volc. Geother. Res., **109**: 55-75.

DELLA VEDOVA B., MONGELLI F., PELLIS G. & ZITO G. (1991) – *Campo regionale del flusso di calore nel Tirreno.* Atti 10° Convegno GNGTS, Roma, 817-825.

DELLA VEDOVA B., BELLANI S., PELLIS G. & SQUARCI P. (2001) - *Deep temperatures and surface heat flow distribution.* In: VAI G.B. & MARTINI L.P. (Ed.): *"Anatomy of an orogen: the Apennines and adjacent Mediterranean basins".* Kluwer Academic Publishers, Dordrecht, The Netherlands, 65-76.

DOGLIONI C. (1991) - *A proposal of kinematic modelling for W-dipping subductions - Possible applications to the Tyrrhenian-Apennines system.* Terra Nova, **3**: 423-434.

DOGLIONI C., CARMINATI E. & BONATTI E. (2003) - *Rift asymmetry and continental uplift.* Tectonics, **22**, 3, 1024, doi:10.1029/2002TC001459.

DOGLIONI C., GUEGUEN E., SABAT F. & FERNANDEZ M. (1997) - *The western Mediterranean extensional basins and the Alpine orogen.* Terra Nova, **9**: 3, 109-112.

DOGLIONI C., GUEGUEN E., HARABAGLIA P. & MONGELLI F. (1999) - *On the origin of W-directed subduction zones and applications to the western Mediterranean.* Geol. Soc. Sp. Publ., **156**: 541-561.

DOGLIONI C., INNOCENTI F. & MARIOTTI G. (2001) – Why Mt. Etna? *Terra Nova*, **13**: 25-31.

DOGLIONI C., MONGELLI F. & PIALLI G.P. (1998) - *Boudinage of the Alpine belt in the Apenninic back-arc.* Mem. Soc. Geol. It., **52**: 457-468.

DOGLIONI C., MONGELLI F. & PIERI P. (1994) - *The Puglia uplift (SE Italy): An anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere.* Tectonics, **13**: 1309-1321.

DOWNES H., THIRLWALL M.F. & TRAYHORN S.C. (2001) - *Miocene subduction-related magmatism in southern Sardinia: Sr-Nd- and oxygen isotopic evidence for mantle source enrichment.* J. Volcanol. Geotherm. Res, **106**: 1-21.

ELLAM R.M., MENZIES M.A., HAWKESWORTH C.J., LEEMAN W.P., ROSI M. & SERRI G. (1988) - *The transition from calc-alkaline to potassic orogenic magmatism in the Aeolian Islands, Southern Italy.* Bull. Volcanol., **30**: 386-398.

FABBRI A. & CURZI P. (1979) - *The Messinian of the Tyrrhenian Sea; seismic evidence and dynamic implications.* Giorn. Geol., **43**(1): 215-248.

FACCENNA C., JOLIVET L., PIROMALLO C. & MORELLI A. (2003) - *Subduction and the depth of convection in the Mediterranean mantle.* J. Geophys. Res., 108, doi:10.1029/2001JB001690.

FACCENNA C., MATTEI M., FUNICIELLO R. & JOLIVET L. (1997) - *Styles of back-arc extension in the Central Mediterranean.* Terra Nova, **9**: 126-130.

FINETTI I. & DEL BEN A. (1986) - *Geophysical study of the Tyrrhenian opening.* Boll. Geofis. Teor. ed Appl., **28**: 75-156.

FINETTI I. & MORELLI C. (1973) – *Geophysical exploration of the Mediterranean Sea.* Boll. Geof. Teor. Appl., **15**(60):

263-340.

FORSYTH D. & UYEDA S. (1975) - *On the relative importance of driving forces of plate motion.* Geophys. J. R. Astron. Soc., **43**: 163-200.

FRANCALANCI L. & SANTO A. (1993) - *Magmatological evolution of Filicudi volcanoes, Aeolian Islands, Italy: constraints from mineralogical, geochemical and isotopic data.* Acta Vulcanol., **3**: 203-227.

FRANCALANCI L., TAYLOR S.R., MC CULLOCH M.T. & WOODHEAD J. (1993) - *Petrological and geochemical variations in the calc-alkaline rocks of Aeolian arc (Southern Tyrrhenian Sea, Italy).* Contrib. Mineral. Petrol., **113**: 300-313.

FREPOLI A., SELVAGGI G., CHIARABBA C. & AMATO A. (1996) - *State of stress in the Southern Tyrrhenian subduction zone from fault-plane solutions.* Geophys. J. Int., **125**: 879-891.

GASPARINI C., IANNACCONE G., SCANDONE P. & SCARPA R. (1982) - *Seismotectonics of the Calabrian Arc.* Tectonophysics, **84**: 267-286.

GASPERINI D., BLICHERT-TOFT J., BOSCH D., DEL MORO A., MACERA P., TELOUK P. & ALBAREDE F. (2000) - *Evidence from Sardinian basalt geochemistry for recycling of plume heads into the Earths mantle.* Nature, **408**: 701-704.

GASPERINI D., BLICHERT-TOFT J., BOSCH D., DEL MORO A., MACERA P. & ALBAREDE F. (2001) - *Upwelling of deep mantle material through a plate window: evidence from the geochemistry of Italian basaltic volcanics.* J. Geophys. Res. **107** (B12) 2367, doi:10.1029/2001JB000418

GIARDINI D. & VELONÀ M. (1991) - *The deep seismicity of the Tyrrhenian Sea.* Terra Nova, **3**: 57-64.

GRIPP A.E. & GORDON R.G. (2002) - *Young tracks of hotspots and current plate velocities.* Geophys. J. Int., **150**: 321–361.

GUEGUEN E., DOGLIONI C. & FERNANDEZ M. (1997) - *Lithospheric boudinage in the Western Mediterranean back-arc basins.* Terra Nova, **9** (4): 184-187.

GUEGUEN F., DOGLIONI C. & FERNANDEZ M. (1998) – *On the post-25 Ma geodynamic evolution of the western Mediterranean.* Tectonophysics, **298**: 259-269.

ISHIKAWA T. & TERA F. (1997) - *Source, composition and distribution of the fluid in Kurile mantle wedge: Constraints from across-arc variations of BINb and B isotopes.* Earth Planet. Sci. Lett., **152**: 123-138.

KASTENS K.A. *et alii* (1988) - *ODP Leg 107 in the Tyrrhenian Sea: Insigths into passive margin and back-arc basin evolution.* Geol. Soc. Am. Bull., **100**: 1140-1156.

KASTENS K.A., MASCLE J. *et alii* (1990) – *Proc. ODP, Sci. Results, 107*: College Station TX (Ocean Drilling Program), 772 pp.

LEEMAN W.P. (1996) - *Boron and other fluid-mobile elements in volcanic arc lavas: Implications for subduction processes.* In: BEBOUT G.E., SCHOLL D.W., KIRBY S.H., PLATT J.P. (Ed.): "*Subduction Top to Bottom*". AGU Monograph, 269-276.

LUSTRINO M., MELLUSO L. & MORRA V. (2000) - *The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy).* Earth Planet. Sci. Letters, **180**: 259-270.

MALINVERNO A., CAFIERO M., RYAN W.B.F. & CITA M.B. (1981) – *Distribution of Messinian sediments and erosional surfaces beneath the Tyrrhenian Sea: geodynamical implications.* Oceanol. Acta, **4:** 489-496.

MALINVERNO A. & RYAN W.B.F. (1986) - *Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere.* Tectonics, **5**: 227-245.

MANTOVANI E. (1982) - *Some remarks on the driving forces in the evolution of the Tyrrhenian basin and Calabrian Arc.* Earth Evol. Sci., **3**: 266-170.

MARANI M. & TRUA T. (2002) - *Thermal constriction and slab tearing at the origin of super-inflated spreading ridge: the Marsili volcano (Tyrrhenian Sea).* J. Geophys. Res., **107** (B2): 2188 doi:1029/2001JB000285.

MARGHERITI L., NOSTRO C., COCCO M. & AMATO A. (1996) - *Seismic anisotropy beneath the Northern Apennines (Italy) and its tectonic implications.* Geophys. Res. Lett., **23**: 2721-2724.

MASCLE J., REHAULT J.P. (1990) – *A revised seismic stratigraphy of the Tyrrhenian Sea: implications for the basin evolution.* In: KASTENS K.A., MASCLE J. *et alii – Proc. ODP, Sci. Results, 107*: College Station TX (Ocean Drilling Program), 617-636.

MATTIOLI M., GUERRERA F., TRAMONTANA M., RAFFAELLI G. & D'ATRI M. (2000) - *High-Mg Tertiary basalts in Southern Sardinia (Italy).* Earth Planet. Sci. Letters, **179**: 1-7.

MAUFFRET A., CONTRUCCI I. & BRUNET C. (1999) - *Structural evolution of the Northern Tyrrhenian Sea from new seismic data.* Mar. Petrol. Geol., **16**: 381-407.

MCDONOUGH W.F. & SUN S.S. (1995) - *The composition of the Earth.* Chem. Geol., **120**: 223-253.

MELE G., ROVELLI A., SEBER D. & BARANZAGI M. (1997) - *Shear wave attenuation in the lithosphere beneath Italy and surrounding regions: tectonic implications.* J. Geophys. Res., **102** (6): 11,863-11,875.

METRICH N., BERTAGNINI A., LANDI P. & ROSI M. (2001) - *Cristallization Driven by Decompression and Water Loss at Stromboli Vocano (Aeolian Islands, Italy).* J. Petrol., **42**: 1471-1490.

MONGELLI F., LODDO M. & CALCAGNILE G. (1975) - *Some observations on the Apennines gravity field.* Earth Planet. Sci. Lett., **24**: 385-393.

MONGELLI F. & ZITO G. (1994) - *Thermal aspects of some geodynamical models of tyrrhenian opening.* Boll. Geof. Teor. ed Appl., **XXXVI** (141-144): 21-28.

MONGELLI F., ZITO G., DELLA VEDOVA B., PELLIS G., SQUARCI P. & TAFFI L. (1991) - *Geothermal Regime of Italy and surrounding Seas.* In: Exploration of the deep continental crust, Springer-Verlag Berlin, 381-394.

MORRA V., SECCHI F.A.G., MELLUSO L. & FRANCIOSI L. (1997) – *High-Mg subduction-related Tertiary basalts in Sardinia, Italy.* Lithos, **40**: 69-91.

MOUSSAT E., REHAULT J.P. & FABBRI A. (1986) - *Rifting et évolution tectono-sédimentaire du Bassin tyrrhenien au cours du Néogène et du Quaternaire.* Giornale Geol., **48** (1/2): 41-62.

NICOLICH R. (1989) - *Crustal structures from seismic studies in the frame of the European Geotraverse (southern segment) and Crop projects.* In: BORIANI A., BONAFEDE M., PICCARDO G.B. & VAI G.B. (Eds.):"*The lithosphere in Italy*". Accad. Naz. Lincei, **80**: 41-61.

NICOLICH R. (2001) - *Deep seismic transects.* In: VAI G.B. & MARTINI I.P. (Eds.): "*Anatomy of an orogen: the Apennines and adjacent Mediterranean basins*". Kluwer Academic Publishers, 47-52, Dordrecht, The Netherlands.

NICOLICH R. & DAL PIAZ G.V. (1992) - *Moho isobaths, Structural Model of Italy. Scale 1:500,000.* Quaderni de "La Ricerca Scientifica", **114** (3): CNR.

OXBURGH E.R. & E.M. PARMENTIER. (1977) - *Compositional and density stratification in oceanic lithosphere; causes and consequences.* J. Geol. Soc. London, **133** (4): 343-355.

PANZA G.F., SCANDONE P., CALCAGNILE G., MUELLER S. & SUHADOLC P. (1992) – *The lithosphere-asthenosphere system in Italy and surrounding regions.* Quaderni de "La Ricerca Scientifica", **114** (3): CNR.

PANZA G.F., PONTEVIVO A., SARAÒ A., AOUDIA A. & PECCERILLO A. (2003) - *Structure of the Lithosphere - Asthenosphere and Volcanism in the Tyrrhenian Sea and surroundings.* This volume.

PAPPALARDO L., PIOCHI M., D'ANTONIO M., CIVETTA L. & PETRINI R. (2002) - *Evidence for Multi-stage Magmatic*

Evolution during the past 60 kyr at campi Flegrei (Italy) Deduced from Sr, Nd, and Pb Isotope Data. J. Petrol., **43**: 1415-1434.

PASCUCCI V., MERLINI S., MARTINI P. (1999) - *Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the Northern Tyrrhenian Sea and western Tuscany (Italy).* Basin Res., **11**: 337-356.

PASQUALE V., VERDOYA M. & CHIOZZI P. (2002) - *A possible mechanism for the thermal asymmetry of the Ligurian basin.* Terra Nova, **14** (6): 484-490.

PATACCA E. & SCANDONE P. (1989) - *Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab.* In BORIANI A., BONAFEDE M., PICCARDO G.B. & VAI G.B. (Eds.): "*The Lithosphere in Italy*". Accademia Nazionale Lincei, **80**: 157-176.

PECCERILLO A. (1998) - *Relationships between ultrapotassic and carbonate-rich volcanic rocks in central Italy: petrogenetic and geodynamic implications.* Lithos, **43**(4): 267-279.

PECCERILLO A. & PANZA G. F. (1999) - *Upper mantle domains beneath Central-Southern Italy, Petrological, geochemical and geophysical constraints.* PAGEOPH, **156**: 421-444.

PIROMALLO C. & MORELLI A. (2003) - *P wave tomography of the mantle under the Alpine-Mediterranean area.* J. Geophys. Res., **108**, B2, 2065, doi:10.1029/2002JB001757.

PLANK K.T. & LANGMUIR C.H. (1988) – *The geochimical compoisition of subducting sediment and its consequences for the crust and mantle.* Chem. Geol., **145**: 325-394.

PLATT J.P. & VISSERS R.L.M. (1989) - *Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar Arc.* Geology, **17**: 540-543.

RECQ M., REHAULT J.P., STEINMETZ L. & FABBRI A. (1984) - *Amincissement de la croute et accretion au centre du bassin tyrrhenien d'apres la sismique refraction. Crustal thinning and accretion in the central Tyrrhenian Basin from seismic refraction studies.* Mar. Geol., **55**(3-4): 409-426.

REHAULT J.P., MASCLE J. & BOILLOT G. (1984) - *Evolution geodynamique de la mediterranee depuis l'Oligocene.* Mem. Soc. Geol. It., **27**: 85-96.

ROLLET N., DÉVERCHÈRE J., BESLIER M.O., GUENNOC P., RÉHAULT J.P., SOSSON M. & TRUFFERT C. (2002*) - Back arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, Western Mediterranean.* Tectonics, **21**, 3, 10.1029/2001TC900027.

ROYDEN L.H. (1993) - *The tectonic expression slab pull at continental convergent boundaries.* Tectonics, **12**: 303-325.

RYAN J.G., LEEMAN W.P., MORRIS J.D. & LANGMUIR C.H. (1996*) - The boron systematics of intraplate lavas: Implications for crust and mantle evolution.* Geochim. Cosmochim. Acta, **60**: 415-422.

RYAN J.G., MORRIS J.D., TERA F., LEEMAN W.P. & TSVETKOV A. (1995) - *Cross-arc geochemical variations in the Kurile arc as a function of slab depth.* Science, **270**: 625-627.

SARTORI R. & ODP LEG 107 SCIENTIFIC STAFF (1989) - *Drillings of ODP Leg 107 in the Tyrrhenian Sea: Tentative Basin Evolution Compared to Deformations in the Surroundings Chains.* In BORIANI A., BONAFEDE M., PICCARDO G.B. & VAI G.B. (Eds.): "*The Lithosphere in Italy*". Accademia Nazionale Lincei, **80**: 139-156.

SAVELLI C. (2002) - *Time–space distribution of magmatic activity in the western Mediterranean and peripheral orogens during the past 30 Ma (a stimulus to geodynamic considerations)* J. Geodynamics, **34**: 99-126.

SCANDONE P. (1980) - *Origin of the Tyrrhenian Sea and Calabrian Arc.* Boll. Soc. Geol. It., **98**: 27-34.

SCROCCA D., DOGLIONI C., INNOCENTI F., MANETTI P., MAZZOTTI A., BERTELLI L., BURBI L. & D'OFFIZI S. (Eds.) (2003) – *CROP Atlas: seismic reflection profiles of the Italian crust.* Mem. Descr. Carta Geol. It., **62**.

SCROCCA D., DOGLIONI C. & INNOCENTI F. (2003) - *Constraints for an interpretation of the italian geodynamics: A review.* In: SCROCCA D., DOGLIONI C., INNOCENTI F., MANETI P., MAZZOTTI A., BERTELLI L. & D'OFFIZI S. (Eds.): "*Crop Atlos: seismic reflection profiles of the italian crust*". Mem. Descr. Carta Geol. It., **62**: 15-46

SELVAGGI G. (2001) – *Strain pattern of the Southern Tyrrhenian slab from moment tensors of deep earthquakes: implications on the down-dip velocity.* Ann. Geof., **44** (1): 155-165.

SELVAGGI G. & CHIARABBA C. (1995) - *Seismicity and P-wave velocity image of the Southern Tyrrhenian subduction zone.* Geophys. J. Int., **121** : 818-826.

SERRI G., INNOCENTI F. & MANETTI P. (2001) - Magmatism from Mesozoic to Present: petrogenesis, time-space distribution and geodynamic implications. In: Vai, G.B.and Martini, I.P. (Eds.): *"Anatomy of an Orogen: the Apennines and the adjacent Mediterranean Basins".* Kluwer Academic Publishers: 77-104, Dordrecht, The Netherlands.

TATSUMI Y. & EGGINS S. (1995) - *Subduction Zone magmatism.* Blackwell, 211 pp.

TONARINI S., LEEMAN W.P. & FERRARA G. (2001a) - *Boron Isotopic Variations in Lavas of the Aeolian Volcanic Arc, South Italy.* J. Volcanol. Geotherm. Res, **110**: 155-170.

TONARINI S., ARMIENTI P., D'ORAZIO M. & INNOCENTI F. (2001b) - *Subduction-like fluids in the genesis of Mt. Etna magmas: evidences from boron isotopes and fluid mobile elements.* Earth Planet. Sci. Lett., **192**: 471-483.

TONARINI S., LEEMAN W.P., CIVETTA L., D'ANTONIO M., FERRARA G. & NECCO A. (2004) - *B/Nb and d11B systematics in the Phlegrean Volcanic District (PVD), Italy.* J. Volcanol. Geoth. Res., **133** (1-4), 123-139.

ZITELLINI N., TRINCARDI F., MARANI M. & FABBRI A. (1986) - *Neogene tectonics of the Northern Tyrrhenian Sea.* Giornale Geol., **48**: 1/2, 25-40.

WRIGHT I.C., PARSON L.M. & GAMBLE J.A. (1996) – *Evolution and interaction of migrating cross-arc volcanism and backarc rifting: An example from the southern Havre through (35°20'-37°S).* J. Geophys. Res., **101**: 22,071-22,088.