

The CROP profiles across the Mediterranean Sea (CROP MARE I and II)

I profili CROP attraverso il Mar Mediterraneo (CROP MARE I e II)

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ABSTRACT - Within the framework of the Italian CROP Project, the CROP MARE I and II sub-projects have been carried out to better define the deep crustal structure and the complex geological settings in the Central Mediterranean offshore (around the Italian Peninsula). With these sub-projects, about 8500 km of NVR crustal seismic profiles has been acquired in the Balearic, Tyrrhenian, Ionian, Pelagian and Adriatic seas.

The seismic reflection data acquisition have been conducted by OGS of Trieste while the data processing has been realised by OGS, ISMES, AGIP and Exploration Geophysics Group (Trieste University). The data acquisition and processing has been performed with standard advanced multifold seismic reflection techniques, properly parametrised for deep crustal penetration. Obtained data quality is fair to good in foreland regions (Adriatic and Pelagian seas), and in part of the deep basins. Tyrrhenian Sea margins, the Corso-Sardinian block and the Calabrian arc, where more complex tectonic setting take place, show data strongly variable from good to poor quality.

In this paper, a short description of some of the most significant explored features is made with exhibition of CROP seismic interpretation examples.

KEY-WORDS: CROP MARE, central Mediterranean, deep seismic exploration.

RIASSUNTO - Nell'ambito del Progetto CROP, i sotto-progetti CROP MARE I e II sono stati realizzati per cercare di definire la struttura crostale profonda e il complesso assetto geologico nei mari circostanti l'Italia. Con questi sotto-progetti sono stati acquisiti oltre 8500 km di sismica crostale a riflessione nel Mar Ionio, Mar Adriatico, Mar Tirreno, Mare Balearico e Mare Pelagico. L'acquisizione dei dati sismici è stata eseguita dall'OGS di Trieste mentre l'elaborazione dei dati è stata realizzata da OGS, ISMES, AGIP e dal Gruppo di Geofisica d'Esplorazione dell'Università di Trieste. L'acquisizione ed elaborazione dati è stata completata con le metodologie standard della sismica a riflessione avanzata multifold opportunamente parametrizzate per una penetrazione crostale profonda. La qualità dei dati ottenuti è da discreta a buona nelle aree di avampaese (Mari Adriatico e Pelagico) ed in parte dei bacini profondi. I margini tirrenici, il blocco Sardo-Corso e l'Arco Calabro presentano dati fortemente variabili da buona a scarsa qualità.

In questo contributo, vengono descritte le principali caratteristiche delle aree indagate e mostrati alcuni esempi dell'interpretazione sismica.

PAROLE CHIAVE: CROP MARE, Mediterraneo centrale, esplorazione sismica profonda

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1. - FOREWORD

Investigations of the Mediterranean Sea using advanced multi-channel stacking seismic techniques started in 1969 in the Tyrrhenian Sea, when the Osservatorio Geofisico Sperimentale of Trieste (OGS) launched its 5-year program to explore the entire Mediterranean Basin (FINETTI *et alii*, 1970; FINETTI & MORELLI, 1972; 1973). The objective of the Mediterranean Sea (MS) Lines project was the reconstruction of the tectono-stratigraphic setting of the sedimentary cover and a regional definition of the involved geodynamics, using record lengths ranging from 6 to 10 seconds (TWT).

Although basically limited to the sedimentary sequence, the MS Lines project revealed for the first time the presence of an old oceanic crust in the Ionian Sea (FINETTI, 1982) and also produced a clear subsurface image of the young oceanic crust in the Tyrrhenian Sea (FINETTI & DEL BEN, 1986). It became clear, however, that in order to further our knowledge of the Mediterranean, seismic exploration would have to extend from middle to deep crustal penetration. This was the origin of the CROP project. The first off-shore seismic line was a joint ECORS-CROP profile acquired in 1988 in the Western Mediterranean, extending from the Gulf of Lyon to the NW margin of Sardinia for a

total of about 400 km, for which CROP Line M-1 contributed about 200 km (FANUCCI, this vol.).

2. - CROP MARE NETWORK

In 1989 CNR, AGIP (Italian Oil Company) and ENEL (Italian National Electricity Authority) agreed to finance a 5-year program of deep crustal seismic sections in the off-shore Central Mediterranean (around the Italian peninsula), as well as connected on-shore lines across the Apennines. Following on the ECORS-CROP M1 line, the CROP MARE project, which is by far the largest part of the CROP network, acquired a total of about 8500 km of deep NVR sections (sections M-2 to M-39), during cruises in 1991, 1993-94 and 1995. The regional distribution of the CROP MARE sections is reported in Table 1 (see also Appendix "Plates enclosed with the CROP Atlas", fig. 1 for a location map of these sub-projects).

3. - SOME RESULTS

The following is a summary of some results obtained from interpretation of the CROP MARE sections, illustrated by a number of examples exhibited in figures 1 to 11.⁽²⁾

Table 1. – *Regional distribution of the CROP MARE sections*
– Distribuzione regionale dei profili sismici CROP MARE

| REGION | CROP M Section or Part of Section (P) | | | | | | | | | | | | TOTAL Sections and Parts |
|--------------------------|---------------------------------------|-----------|------------|------------|-----|-----|-----|------------|-----|-----|----|----|--------------------------------|
| | 13 | 14 | 15 | 16 | 17A | 17B | 17C | 18 | | | | | |
| ADRIATIC SEA | 13 | 14 | 15 | 16 | 17A | 17B | 17C | 18 | | | | | 8 |
| LIGURIAN SEA | 10 (P) | 11 | 2 | | | | | | | | | | |
| TYRRHENIAN SEA | 2A (P) | 6A | 613 | 9 | 26 | 27 | 28A | 28B | 29A | 29B | 30 | 36 | 12 |
| IONIAN SEA | 2B | 3 | 4 | 5 | 8 | 21 | 22 | 23A (P) | 31 | 34 | 38 | | 11 |
| PELAGIAN SEA | 23A (P) | 24 | 25 | 39 | | | | | | | | | 4 |
| TUSCAN ARCHIPELAGO | 10 (P) | 11 | 12A | 12B (P) | 37 | | | | | | | | 5 |
| SARDINIAN CHANNEL | 23B | 32 | | | | | | | | | | | 2 |
| CORSO-SARDINIAN BLOCK | 1 (P) | 2A (P) | 12B (P) | | | | | | | | | | 3 |
| BALEARIC SEA | 1 (P) | 2A (P) | | | | | | | | | | | 2 |

⁽²⁾ This Atlas shows only a few examples of interpreted CROP MARE sections. The interpretation of the entire CROP MARE data-set, including all reprocessed sections and connected onshore CROP sections, will be published by Elsevier Science in a forthcoming volume entitled "CROP - Crustal Seismic Exploration of the Mediterranean Region" (I. R. FINETTI, Editor).

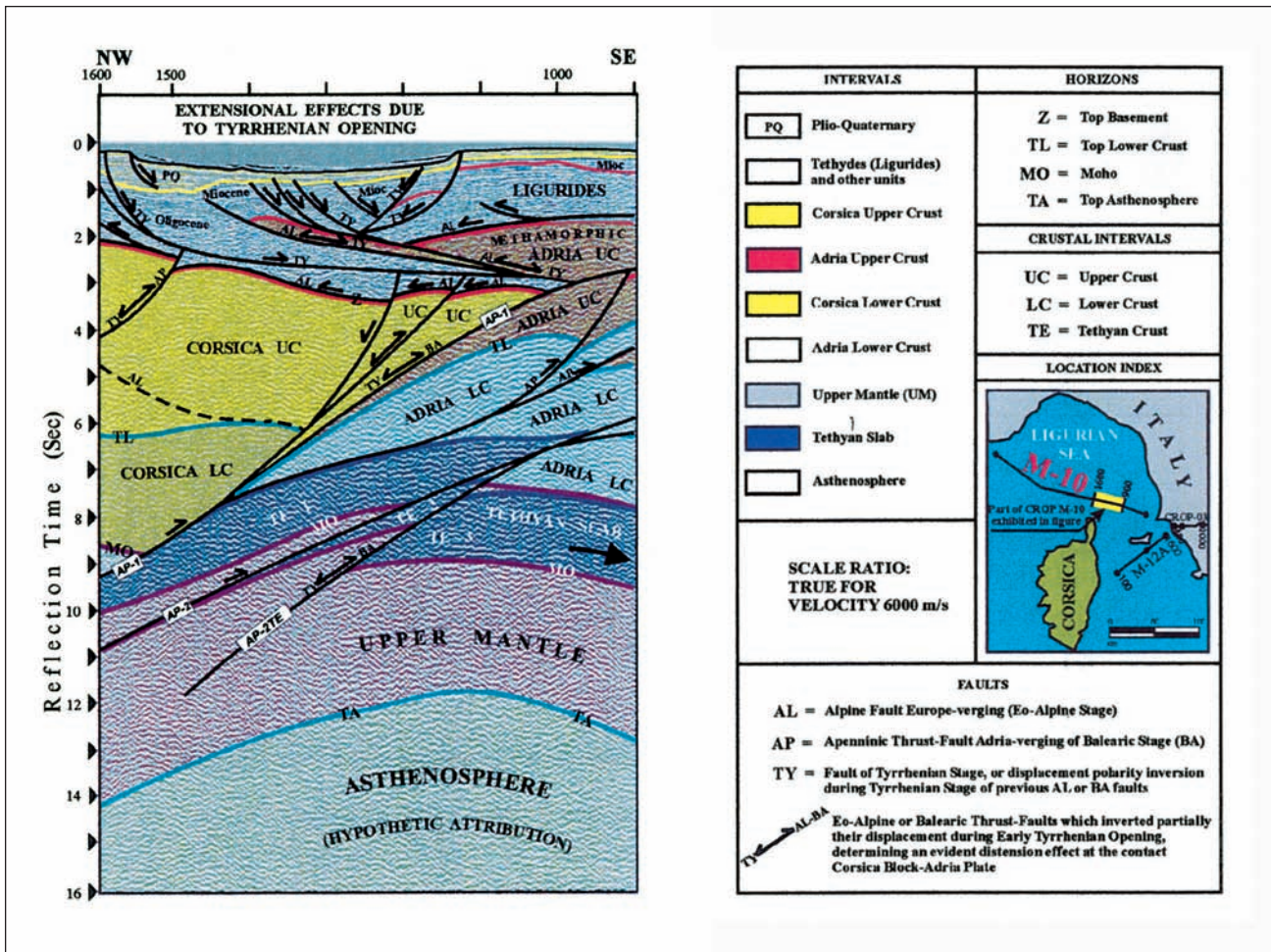


Fig. 1 - Part of the reprocessed and interpreted CROP M-10 in the Tuscan Archipelago - East Corsica Block off-shore area, showing the collisional contact between the rotated Corsica Block and the Adria margin. Derived segment of a figure after FINETTI *et alii* (2001).

- Porzione, riprocessata ed interpretata, della linea CROP M-10 nell'arcipelago Toscano - zona orientale del blocco Corso; è mostrato il contatto collisionale tra il blocco Corso ruotato e il margine di Adria. Ripreso da FINETTI *et alii* (2001).

3.1. - M-2 SECTION

This is the longest CROP MARE section of the project. It starts within the Balearic Sea, crosses the entire Corso-Sardinian Block, all of the Tyrrhenian Sea up to the Calabrian coast (M-2A), and, after a break in the Strait of Messina, continues into the Ionian Sea (M-2B). This second part of the section explores the thick wedge of the Calabrian Arc and the subducting Ionian oceanic crust and its condensed Mesozoic-Tertiary cover.

The decision to cross the Corso-Sardinian Block through the channel of water between the two islands (Bocche di Bonifacio) (M-2A) was taken because of the much cheaper cost of this option and the better seismic response with respect to the on-shore line initially proposed as the continuation of line M-1 (CROP-ECORS: Section Gulf de Lyon - NW Sardinian coast). The M-2A section provides a

clear image, for the first time, of the crustal tectono-stratigraphy of the Corso-Sardinian Block. The M-2A section also clearly reveals: a) the listric faults of the Balearic margin of the Corso-Sardinian Block; b) the extensional tectonics superimposed on previous compressive deformations on the Tyrrhenian margin; c) the oceanic crust of the Tyrrhenian Sea; d) the upper part of the subducting Ionian slab. The inner sector of the Calabrian Arc, on M-2A, and the thick Calabrian wedge into the Ionian Sea (M-2B) are imaged fairly well (see sections in the Atlas).

3.2. - LIGURIAN SEA SECTIONS (M-10 & M-11)

These two sections provide useful information on the crustal opening of the Ligurian Sea, the collisional tectonics between the Corsica and northwestern Adria plates, and the tectono-strati-

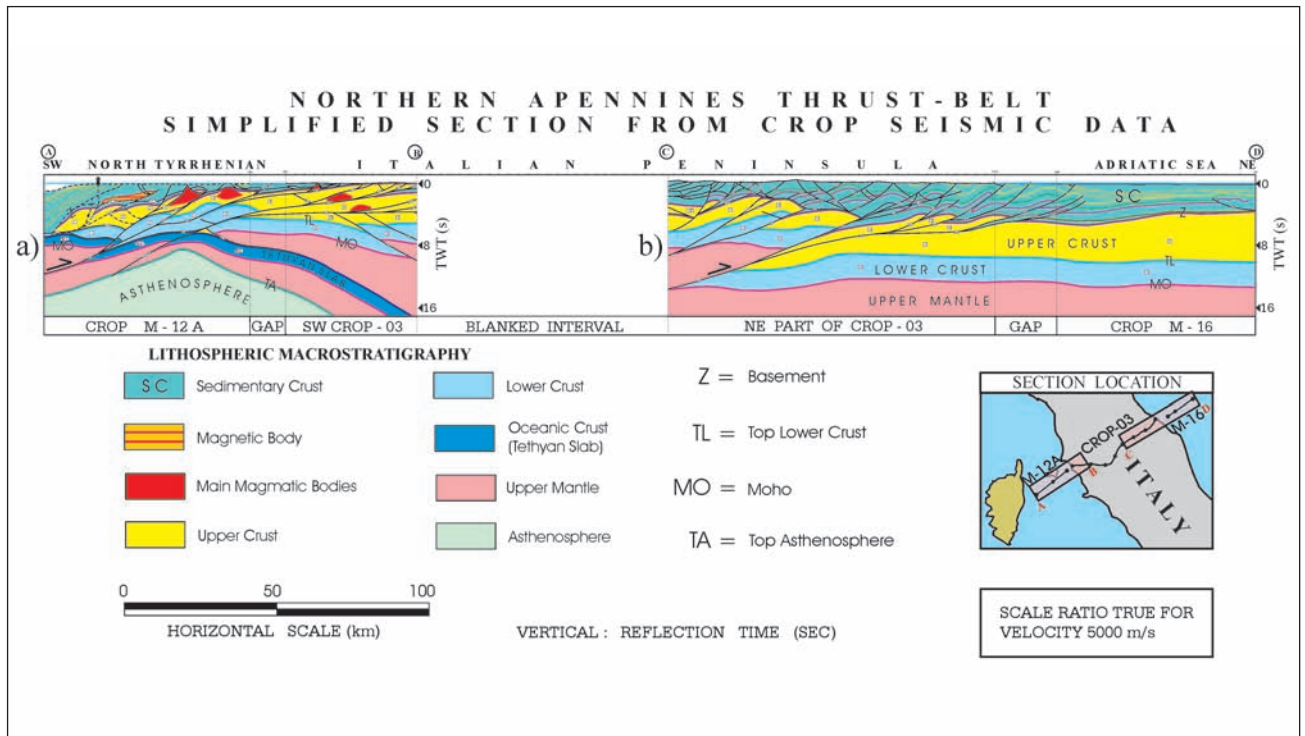


Fig. 2 - Simplified version of the reconstructed seismo-geological cross-section on CROP M-12A and M-16 and adjacent part of CROP 03. Reduced version of a complete section from FINETTI *et alii* (2001).

- *Versione semplificata della sezione seismo-geologica basata sulle linee CROP M-12A e M-16 e su porzione adiacente del CROP 03. Versione ridotta della sezione contenuta in FINETTI *et alii* (2001).*

graphic setting of the northward continuation of the Corsica Block (fig. 1). There is good evidence from these data that the Alpine Tethys slab was subducted beneath the Adria Plate during the Eo-Alpine stage. Crustal thrust faults of European vergence (Eo-Alpine stage) are truncated by thrust faults of opposite polarity, which were generated during the opening of the Balearic Sea (Upper Oligocene–Lower Miocene). The extensional tectonics related to the opening of the Tyrrhenian Sea, which is well developed towards the south, in the Corsica basin, is a minor fact.

In the deeper part of sections M-10 and M-11 it is possible to identify a doming reflector that has been attributed to the top of the asthenosphere. Detailed seismic imaging of this lithospheric thinning has revealed that the topmost part of the dome is some 4 to 5 km higher than the rough depth obtained from surface wave dispersion data.

3.3. - SECTIONS M-12A & M-16, THE CONTINUATIONS OF CROP03 OF THE NORTHERN APENNINES; THE TUSCAN ARCHIPELAGO SECTIONS M-12B & M-37

CROP MARE sections M-16 and M-12A are extensions of the on-shore section CROP03 of the

Northern Apennines into the Adriatic Sea and the Tuscan Archipelago, respectively. Total length of the three sections is about 400 km. Section M-16 exhibits the frontal thrusts of the Northern Apennines (fig. 2b) and allows us to identify the Moho discontinuity and the top of the lower crust, which are normally better defined seismically in the Adriatic Sea than in the adjacent on-shore belt.

Section M-12A investigates the Tuscan Archipelago, which is a complex and crucial part of the inner Northern Apennines that was affected by a number of important geodynamic events that have left their imprint (FINETTI *et alii*, 2001). After a first Eo-Alpine stage, during which the Alpine Tethys was subducted beneath the Adria (figs. 1, 2a) and Europe-verging thrust faults originated, the second stage was characterized by the opening of the Balearic Sea (Late Oligocene–Early Miocene), the rotation of the Corso-Sardinian Block, and the formation of Adria-verging shear and thrust planes. Extension of the CROP 03 onto the Tuscan archipelago has provided images of the first lithospheric root of the Northern Apennines and has solved the problem of whether the Alpine Tethys was subducted beneath the European plate (SERRI *et alii*, 1993) or the Adria plate (FINETTI *et alii*, 2001). Evidence of the subduction of

the Alpine Tethys beneath the Adria can also be seen in the CROP – ECORS profile of the Western Alps (ROURE *et alii*, 1996).

Prominent low-angle compressive shear-plane tectonics took place during the Balearic stage (Upper Oligocene-Lower Miocene). In the Tuscan Archipelago zone the east-verging thrust deformations also affected the lower crust of the Adria plate and the subducted Alpine Tethys slab, but were confined to the upper crust of the Adria in the on-shore area. The prominent lithospheric high-angle thrust fault that displaces the Moho by about 47 km horizontally and roughly 14 km vertically is shown in figure 2b. This main Northern Apennine fault, generated during the Tyrrhenian stage (Upper Miocene to Present), splays outwards to the front of the belt in the Adriatic Sea.

3.4. - TYRRHENIAN SEA SECTIONS (M-2A; M-6A, B; M-9; M-26; M-27; M-28A, B; M-29A, B; M-30 & M-36)

Since the Tyrrhenian Sea area contains a large part of the information that is crucial to our understanding of several tectono-dynamic events that occurred in the Central Mediterranean, 12 regional CROP sections were performed in the Tyrrhenian Sea area and on its complex margins (Table 1). Due to the intense degree of tectonization, the seismic response of the Tyrrhenian and Calabrian Arc sections lacks homogeneity and is unsatisfactory in specific zones. There-

fore, nearly 2760 km of Tyrrhenian and Ionian sections were carefully reprocessed by the Exploration Geophysics Group of the University of Trieste (DISGAM, Faculty of Sciences). A significant improvement was achieved and selected results from these reprocessed sections will be published by Elsevier Science in a monographic volume entitled “CROP, Deep Seismic Exploration of the Mediterranean Region” (Ed.: I. R. FINETTI).

3.4.1. - *Latial-Campanian Margin*

The eastern margin of the deep Tyrrhenian Sea was explored by five CROP MARE sections: M-9, M-29B, M-30, M-6B, and M-36 parallel to the coast. In the three most homogeneous sections perpendicular to the coast (M-29B, M-30 and M-6B) we can recognize a common stack of tectonic units and, from the Tyrrhenian network of the CROP MARE sections, we can reconstruct their original paleogeographic position. On the Latial -Campanian border we can distinguish, from west to east, the following three main stacked tectonic units (fig. 3):

- a) A fragment of the European Crust (Calabrides), covered by Plio-Pleistocene sediments or, more externally, by the Alpine Tethydes (Ligurides), overlain by Upper Pliocene-Pleistocene sediments. This fragment is considered the frontal thrust system of the Corso-Sardinian Block, emplaced during its anti-clockwise rotation (Balearic stage). In the Upper Miocene the open-

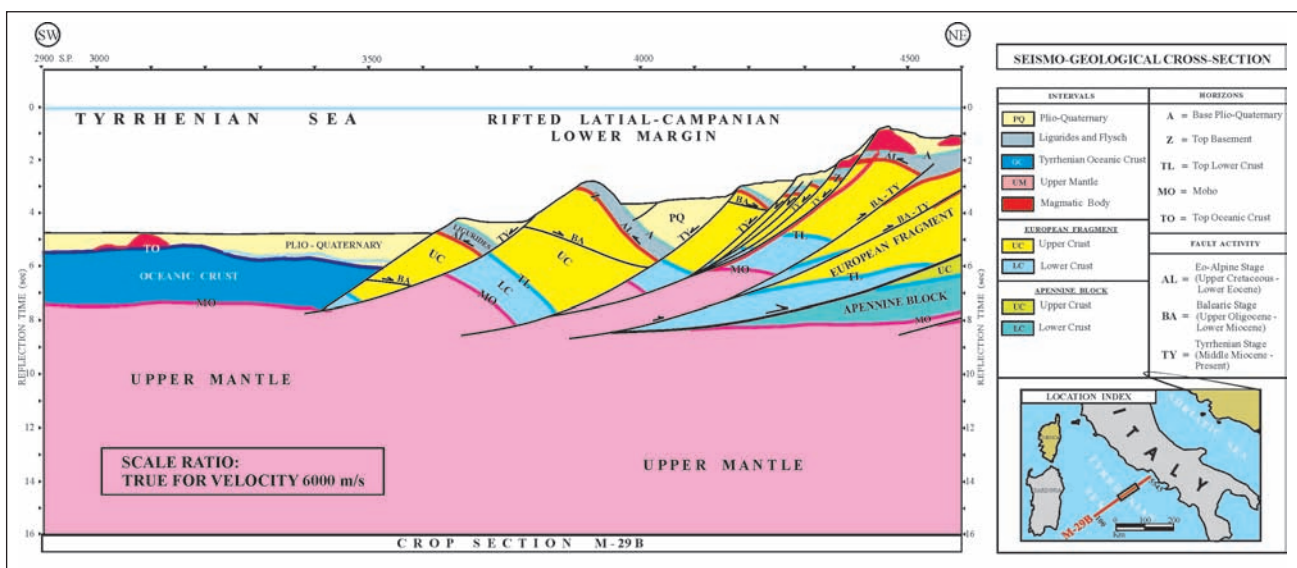


Fig. 3 - Part of the reconstructed crustal seismo-geological cross-section on the Latial-Campanian margin of the Tyrrhenian Sea. Section is based on CROP MARE M-29B (part).

- *Porzione della sezione seismo-geologica ricostruita lungo il margine campano-laziale del Mar Tirreno. Sezione basata su CROP MARE M-29B (parte).*

ing of the Tyrrhenian Sea detached this chain fragment and started to tectonically transport it southeastwards. The lower crust section also took part in this migration.

- b) A fragment composed of thrust blocks of a Mesozoic Platform (Apennine Platform) and its upper and lower crust. Fragment a) collided with fragment b) and thrust it into oblique convergence. The stack of Calabrides and the Apennine platform then moved ESE.
- c) The Western Margin of the Adria Plate, deformed by compressive tectonics and obliquely thrust by fragments a) and b), accompanied by left lateral strike-slip and transform faults. In the Late Tyrrhenian stage (last 3.5 - 0.5 Ma.) the western extremity of the Latial-Campanian marginal stack was affected by prominent extensional tectonics with the generation of some major listric faults (fig. 3)

Sea are quite similar to those described for the Latial-Campanian margin. The most important difference is in the paleogeographic provenance of the internal thrust platform block represented by the Panormides. These tectonic units were probably detached from a promontory of the African Plate located more or less immediately SE of Sardinia and delimiting at its NE border the Ionian Sea and at its NW edge the Alpine Tethys. During the closing part of the Balearic stage the rotation of the Corso-Sardinian block collided with the promontory of the African plate (FINETTI *et alii*, in press), thrusting it, and detaching and pushing eastwards the Panormides (including their upper and lower crust). These stacked blocks were first thrust onto the Ionian oceanic crust with a W-E polarity. Then, with the opening of the Tyrrhenian Sea, the Calabrides (fig. 4), Panormides and Ionian Tethydes were obliquely transported towards the southeast onto the margin of northern Sicily (by the mantle flow induced by the sinking of the Ionian slab). A prominent NW-SE en-echelon right transcurrent system characterizes the movement of Northern Sicily and its Tyrrhenian margin (FINETTI *et alii*, 1996).

Sections M-6A, M-26, M-28A, M-28B (in part)

3.4.2. - Sicilian Margin of the Tyrrhenian Sea

The basic style and the stacked tectonic elements of the Sicilian margin of the Tyrrhenian

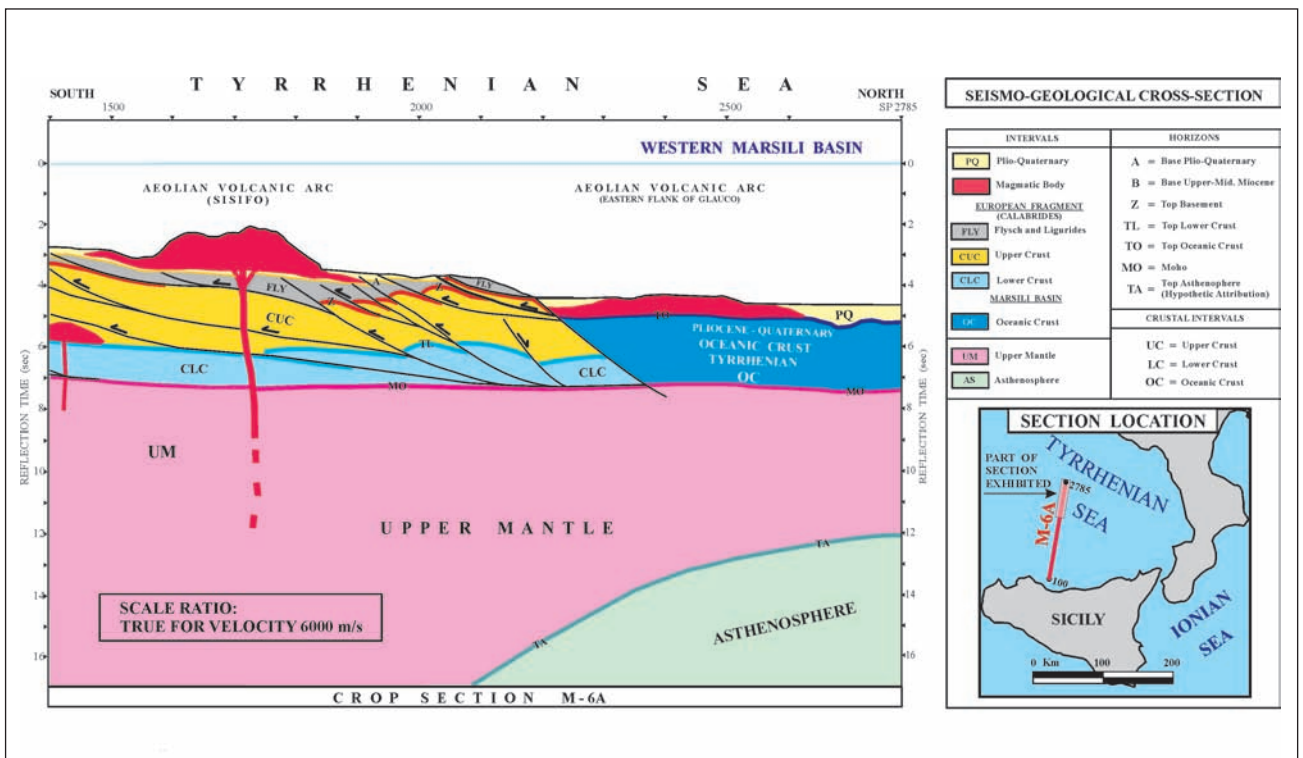


Fig. 4 - Reconstructed lithospheric section of the Southern Tyrrhenian Sea, at the boundary between the Marsili and Issel basins. Reflection horizon "TA", typical of most Tyrrhenian CROP MARE sections, is tentatively attributed to the top of the asthenosphere.

- Ricostruzione di una sezione litosferica del Mar Tirreno meridionale, al confine tra i bacini del Marsili e di Issel. L'orizzonte "TA", tipico di molte sezioni tirreniche del CROP MARE, è tentativamente attribuito al top dell'astenosfera.

and M-29A show the tectonic evolution of this complex region. The paleo-boundaries of the Ionian Sea and the Upper Ionian slab can be identified, and, by restoring the crustal shortenings, we can reconstruct their paleogeography.

3.4.3. - Sardinian Margin of the Tyrrhenian Sea and Sardinian Channel zone

CROP MARE section M-28B provides a seismic image of the crust of the Tyrrhenian margin of the Sardinian Block. From the coast to the Ogliastro basin the thick existing crust shows the most impressive extensional (listric) faults of the Tyrrhenian stage. In the lower crust of this area we can also distinguish thrust faults of probable Upper Oligocene-Lower Miocene age, which splayed upwards and eastwards, with clear subsurface imaging in the segment of the section running from shot-point (SP) 100 to 3000. From SP 2400 through most of the remaining part of section M-29B, the opening of the Tyrrhenian Sea has prominently distended the crust, which assumes the characteristics of a very thin delaminated continental crust. The distended crust belongs mostly to the domain of the Calabrides. The extensional rate of the thinned Tyrrhenian margin, on the basis of realistic volumetric calculations, can be estimated in the order of four times that of the original Middle-Lower Miocene Balearic wedge.

Sections M-23B and M-32 investigated the Sardinian Channel. The former terminates in the south-easternmost part of the Balearic basin, with oceanic crust. Section M23B then crosses the extended Balearic margin and the collisional zone between the Sardinian block and the African margin. The northern part of Section M-32 shows thrust blocks of the Calabrides and their cover, while the southern part images the compressive deformation of the innermost Maghrebides.

3.5. - IONIAN SEA SECTIONS (M-2B; M-3, M-4; M-5; M-8; M-21, M-22, M-23A PART; M-31; M-34 & M-38)

The eleven CROP MARE sections of the Ionian Sea provide important information on this area. For example, they have confirmed the crustal character of the deep basin, which FINETTI (1982) had proposed as an old oceanic crust on the basis of "MS" seismic lines. From the Ionian and Tyrrhenian CROP MARE data-set, starting from the undeformed remnant Ionian Ocean, it is possible to define the Apulian and

| CONDENSED SEQUENCE OF THE IONIAN TETHYS | | | | | |
|---|--|------------------------|--|--|-----------|
| COLUMN (NOT TO SCALE) | AGE | FORMATION | LITHOLOGY | INDICATIVE THICKNESS (m) | |
| | OLIGOCENE | M. MALOMO | Black Argillites | 70 - 80 | |
| | EOCENE | SCAGLIA | Deep Deposition Limestone | 70 - 80 | |
| | CRETACEOUS | GALESTRINE BLACK SHALE | Alternate calcareous shales and argillites with chert and radiolarians | 200 - 220 | |
| | JURASSIC | SILICEOUS SCHISTS | Siliceous Shales and Radiolarites | 80 - 120 | |
| | TRIAS | UPPER | CHERTY LIMESTONE | Thin stratification of cherty limestone | 300 - 350 |
| | | MIDDLE | M. FACITO | Ladinian argillites with Anisian blocks of carbonate and chert | 80 - 100 |
| | TOTAL THICKNESS OF THE CONDENSED IONIAN SEQUENCE | | | 800 - 950 | |

Fig. 5 - Reconstructed condensed sequence of the Ionian Tethys (or Ionides) from the Lagonegro area. This succession was detached from the subducted Ionian slab and tectonically transported onto the Apulian platform during the Plio-Quaternary by oblique ramps and thrusting process. The interpreted seismic stratigraphy of the undeformed Ionian Ocean attributes these condensed flat deposits to a period running from the Middle Trias to the Oligocene. An average reflection time-interval of 0.35-0.40 s TWT is seismically imaged. A thinner situation can be seen on an embryonic Ionian ridge.

- Ricostruzione di una serie condensata della "Tetide Ionica" (o Ionidi) derivata dall'area lagonegrese. Questa successione è stata scollata dallo slab Ionico in subduzione e trasportata tettonicamente sopra la piattaforma apula, durante il Plio-Quaternario, da fenomeni di sovrascorrimento. L'interpretazione sismica di questa successione stratigrafica permette di attribuire questi depositi condensati ad un periodo compreso tra Trias medio e l'Oligocene. Uno spessore medio in tempi doppi di 0.35-0.40 s è rappresentato nei dati sismici. Spessori minori possono essere riconosciuti su una embrionale dorsale ionica.

North-African paleomargins, also beneath the Calabrian arc. Considering the crustal shortening in the Tyrrhenian area, and deleting the stacked blocks that migrated from outside this area, we can recognize the paleogeography of the Ionian Ocean (neo-Tethys) that opened between Adria and Africa and the seismic image of the upper Ionian slab. The segmented shape of the Paleo-Ionian margins along the western Adria plate fits fairly well with that obtained on the African margins (FINETTI & DEL BEN, 2000). Such a paleogeography is very helpful for understanding and reconstruction of the kinematic process that occurred during the detachment of the Adria plate and opening of the Ionian-East Mediterranean Seas (neo-Tethys). Limiting our observations to the condensed deep-water Ionian cover sequence (fig. 5), thrust onto the Apulian plate in the Southern Apennines (Lagonegro sequence), we could conclude that the Ionian opening occurred in the Middle Triassic, as testified by the age of the known basal formation (Mt. Facito). However, if we consider a wider neo-Tethyan area, from the Oman to the Ionian Sea, we could infer that the Ionian opening started during the Permo-

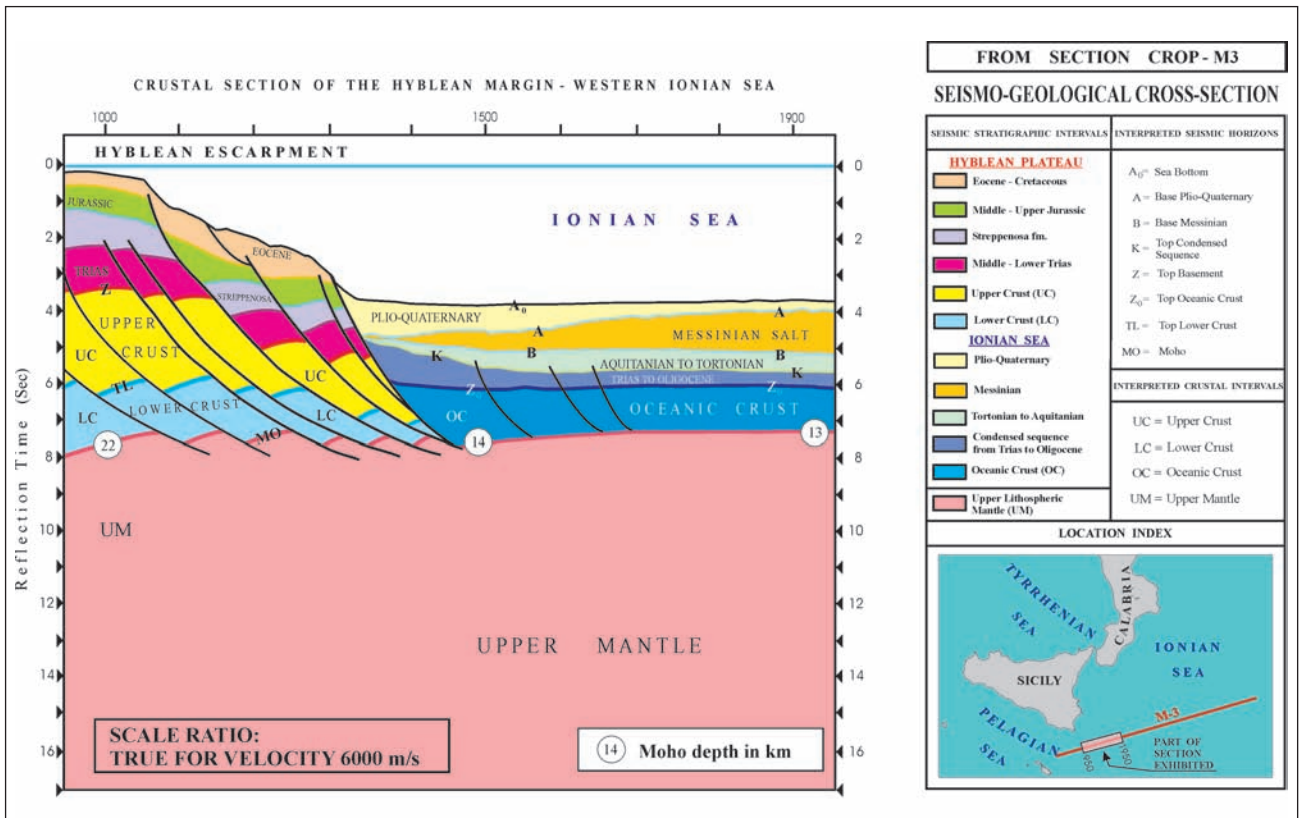


Fig. 6 - Interpreted CROP section M-3 (part) across the Hyblean Margin-Western Ionian Sea. It shows the condensed sedimentary Middle Trias-Oligocene interval, followed by an Aquitanian to Tortonian interval of higher sedimentation rate, a thick Messinian salt deposit and a thin Plio-Quaternary interval. Crustal depths (km) of the Moho are indicated in the white circles. The lithology of the condensed sequence, reconstructed from Lagonegro area in the Southern Apennines, is shown in fig. 5. The total thickness of the condensed deep-water deposit covering the oceanic Ionian crust is less than 1 km. The reflection time interval of about 0.3 - 0.4 s is in agreement with the low value for total thickness of the Lagonegro unit. Prominent thrusting of Ionian Tethydes (or Ionides) occurred both in the Southern Apennines and in Sicily.

- Interpretazione della sezione M-3 (parte) attraverso il margine tibeo-Mar Ionio occidentale. È rappresentata la successione condensata del Trias medio-Oligocene seguita da un intervallo Aquitaniano-Tortoniano, caratterizzato da tassi di sedimentazione maggiori, da un elevato spessore di evaporiti del Messiniano e da sottile intervallo Plio-Quaternario. La profondità della Moho è riportata nei cerchi bianchi. Le litologie della successione condensata ricostruite dall'area lagonegrese nell'Appennino meridionale, sono illustrate in fig. 5. Lo spessore totale dei depositi condensati di acque profonde che ricoprono la crosta oceanica ionica è meno di 1 km. Lo spessore in tempi di circa 0.3 - 0.4 s è in accordo con i ridotti spessori complessivi delle unità lagonegresi. Cospicui fenomeni di sovrascorrimento delle Ionidi sono avvenuti sia nell'Appennino meridionale che in Sicilia.

Trias (STAMPFLI & MOSAR, 1999; STAMPFLI, 2000; FINETTI & DEL BEN, 2000). The lack of Permian-Lower Triassic deposits in the Lagonegrese sequence may be explained by the occurrence of a certain diachrony between the Oman sector and the north-western extremity of the neo-Tethys, or, in alternative, by tectonic dispersion. Petrological studies on the Ivrea zone (Paleo-African plate border before the Ionian opening) demonstrate that a prominent extensional tectonics occurred in the lower crust during the Permian, accompanied by syn-magmatic mafic intrusions (QUICK *et alii*, 1992; VOSHAGE *et alii*, 1990).

The Hyblean - Maltese escarpment constitutes a preserved Ionian margin that has not yet been deformed by the south-eastern migration of the Calabrian arc. CROP MARE sections M-3, M-21 and M-23A cross the area connecting the Hyblean Plateau to the Ionian ocean crust. The interpreta-

tion of this junction zone is exhibited in figure 6 (section M-3 in part), where listric faults of the crustal opening are quite evident. As regards the age of the tectonic activity, fault re-activation took place in the Middle Jurassic (Atlantic opening), after the Permo-Triassic opening. The subsequent renewed activation of old faults and the generation of new faults are due to a disturbance of the isostatic equilibrium of the area triggered by the wedge thickening of the Calabrian and Hellenic arcs.

There is a wealth of material in the literature on the Calabrian and Hellenic arcs. For a number of years new geophysical surveys, and seismics in particular, have contributed significantly to defining the regional tectono-stratigraphic setting of the Hellenic arc, including its outer zone (Mediterranean Ridge; FINETTI, 1976), and of the Calabrian arc (FINETTI & DEL BEN, 1986). The CROP MARE sec-

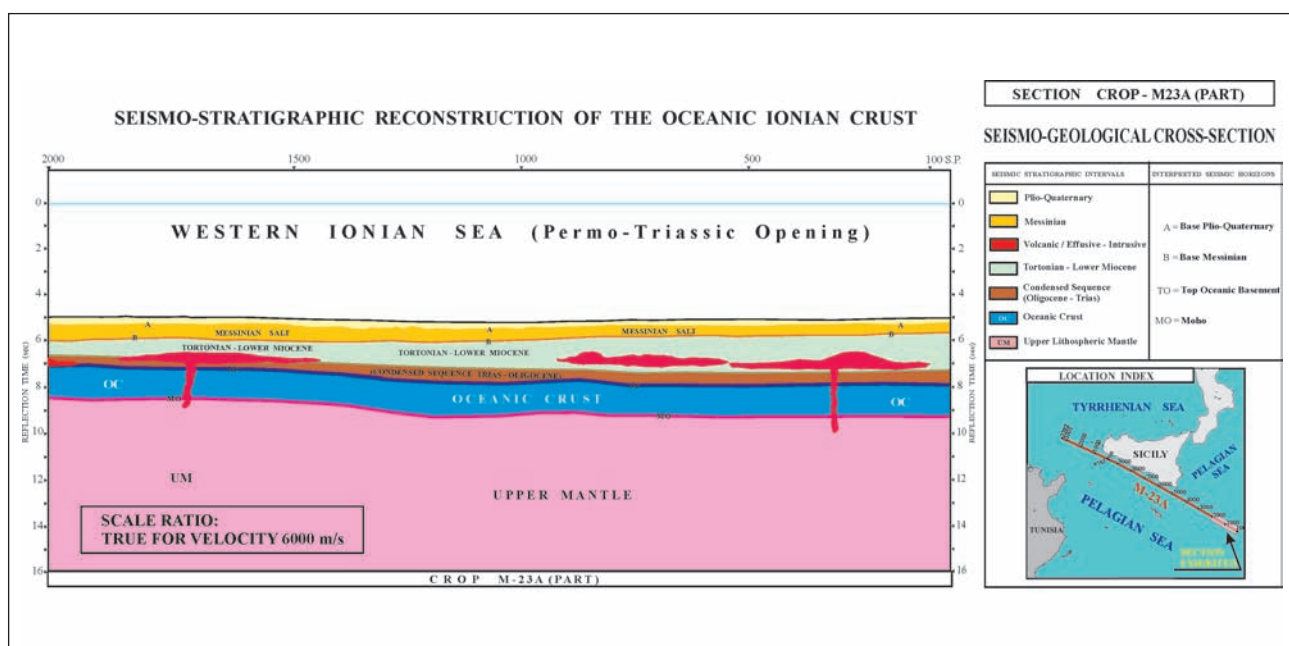


Fig. 7 - Interpreted seismic stratigraphy of the sedimentary cover and of the oceanic crust of the western Ionian abyssal plain. The old oceanic crust, about 1.6 s (twf) thick in this area (about 5.5 km), is overlain by condensed flat sedimentary units of 0.8 - 1.0 km thickness, deposited from Trias to Oligocene. A higher sedimentation rate followed from the Lower Miocene to Tortonian, when the orogenic activity triggered an increased rate of deposition. A relatively thick Messinian salt layer and thin Plio-Quaternary deposit close the sequence. Magmatic effusions, mostly of Miocene age, are seismically evident.

- Interpretazione della stratigrafia sismica della copertura sedimentaria e della crosta oceanica del settore occidentale della piana abissale ionica. La vecchia crosta oceanica, spessa circa 1.6 s (twf) in questa area (corrispondenti a circa 5.5 km), è ricoperta da unità sedimentarie sub-orizzontali caratterizzate da spessori di 0.8 - 1.0 km che si sono depositate dal Trias all'Oligocene. Tassi di sedimentazione più elevati si sono registrati dal Miocene inferiore al Tortoniano a seguito dell'attività orogenica. Uno livello di sale Messiniano di spessore relativamente elevato e un sottile intervallo di depositi Plio-Quaternari chiudono questa successione. Effusioni magmatiche, prevalentemente di età miocenica, sono anche evidenti nella sezione sismica.

tions have added some important information that was until now missing (see southern part of CROP M-2A and M-2B sections in this Atlas).

The seismic stratigraphy of the undeformed Ionian abyssal plain area is well imaged in figures 5, 6 and 7, which are self-explanatory. The thicker Messinian salt deposit in the eastern part of figure 6 is due to the cumulative effect of the southeastwards push of the Calabrian arc. The correct value for a standard salt deposit thickness in the undeformed Ionian basin is that imaged in figure 7.

The reconstruction of the condensed sedimentary sequence of the Lagonegrese area shown in the column in figure 5 fits very well with our interpretation of the seismic stratigraphy of the deep Ionian basin.

3.6. - PELAGIAN SEA SECTIONS (M-3 IN PART; M-23A, M-24; M-25 & M-39)

As mentioned in the previous section, at the eastern edge of the Pelagian Sea it is possible to observe major listric faults associated with the

opening of the Ionian Sea. These faults delimit the eastern boundary of the Pelagian Sea (fig. 6). The seismic stratigraphy of the Pelagian Sea, in major troughs areas, reveals layers attributed to a basal clastic Permian-Early Triassic deposit. In the Southern Pelagian Sea (Tripolitania Basin), sedimentation began in the Lower Paleozoic when the huge regional Gafsa-Jeffara extensional fault became active. The thick carbonatic and evaporitic Triassic deposition that followed the basal clastic sequence is identifiable all over the Pelagian Sea. The thick Triassic platform deposits are followed by several units of Jurassic, Cretaceous and Tertiary-Quaternary age (fig. 8).

One of the most important tectono-sedimentary events in the north-eastern Pelagian Sea is the formation of a rift basin, filled by euxinic deposits (Streppenosa fms) ranging from the Norian to the Hettangian. The basically tabular regional morphology of the Pelagian Sea is interrupted by a NW-SE right transcurrent system that left a prominent tectonic imprint on almost the entire region. Pantelleria, Linosa, Medina and Jarrafa grabens, for example, are major pull-apart basins generated by this

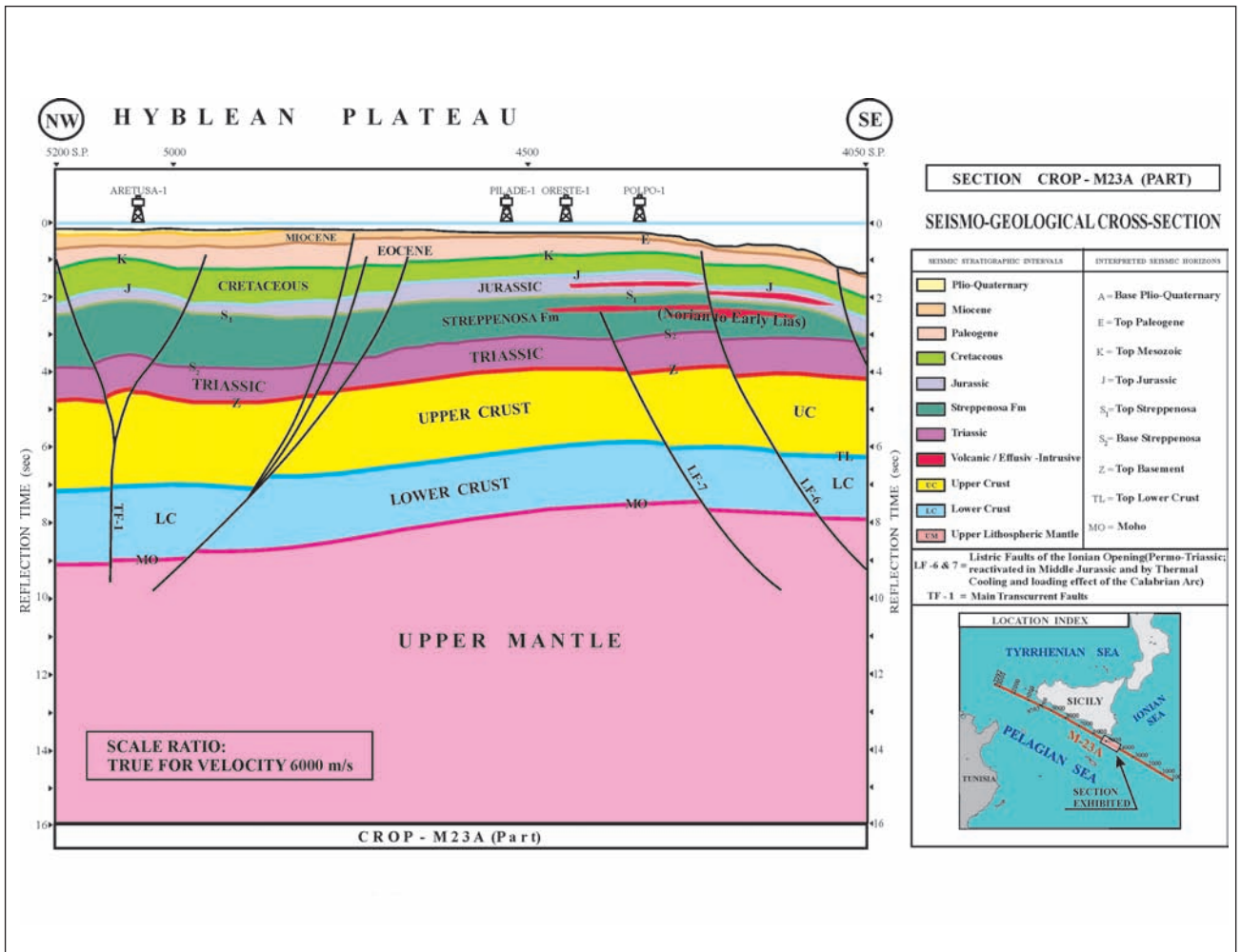


Fig. 8 - Part of the interpreted section M-23A across the Hyblean Plateau (Pelagian Sea). The Aretusa structure represents a NNE-SSW crustal transpressive feature generated by a strike-slip fault system that is antithetic to the main NW-SE right transcurrent system of the Pelagian Sea.

- Porzione interpretata della sezione M-23A attraverso il Plateau Ibleo. La struttura di Aretusa rappresenta un altro transpressivo crostale, orientato NNE-SSW, generato da un sistema di faglie trascorrenti antitetico rispetto al sistema principale trascorrente NW-SE.

transcurrent system. Associated antithetic elements of this tectonic activity are the NNE-SSW left transcurrent fractures that generate widespread flower features. The large Sciacca transpressive crustal flower shown in figure 9 (an interpreted segment of section M-23A) can undoubtedly be ascribed to this origin. In the sedimentary cover this flower structure may be confused as thrust deformation (CATALANO *et alii*, 2000).

3.7. - ADRIATIC SEA SECTIONS (M-13; M-14, M-15; M-16; M-17A; M-17B, M-17C & M-18)

Sections M-17 A, B & C explored the axial zone of the Adriatic Sea from Venice to the Pescara basin. Four sections (M-13, M-15, M-16 & M-18) run trans-

versal to the NW-SE Adriatic axis. Because of military restrictions during the war sively explored by petroleum companies, with the result that the distribution of the main platform and basin formations is regionally known. However, only now the pre-sedimentary upper crust, the lower crust and the Moho are clearly imaged by the CROP MARE sections.

Figure 10 illustrates the crustal tectono-stratigraphy of the Northern Adriatic Sea. It is clear from this section that the upper crust thins out eastward from 6 to 4.5 s; more internally it thins out for up to more than 2.5 seconds with respect to the Adriatic axial zone. The lower crust, on the contrary, keeps a more or less constant thickness (about 3 s).

On sections M-17A, M-17B and the northern part of the M-17C, as well as on M-14, M-15 and

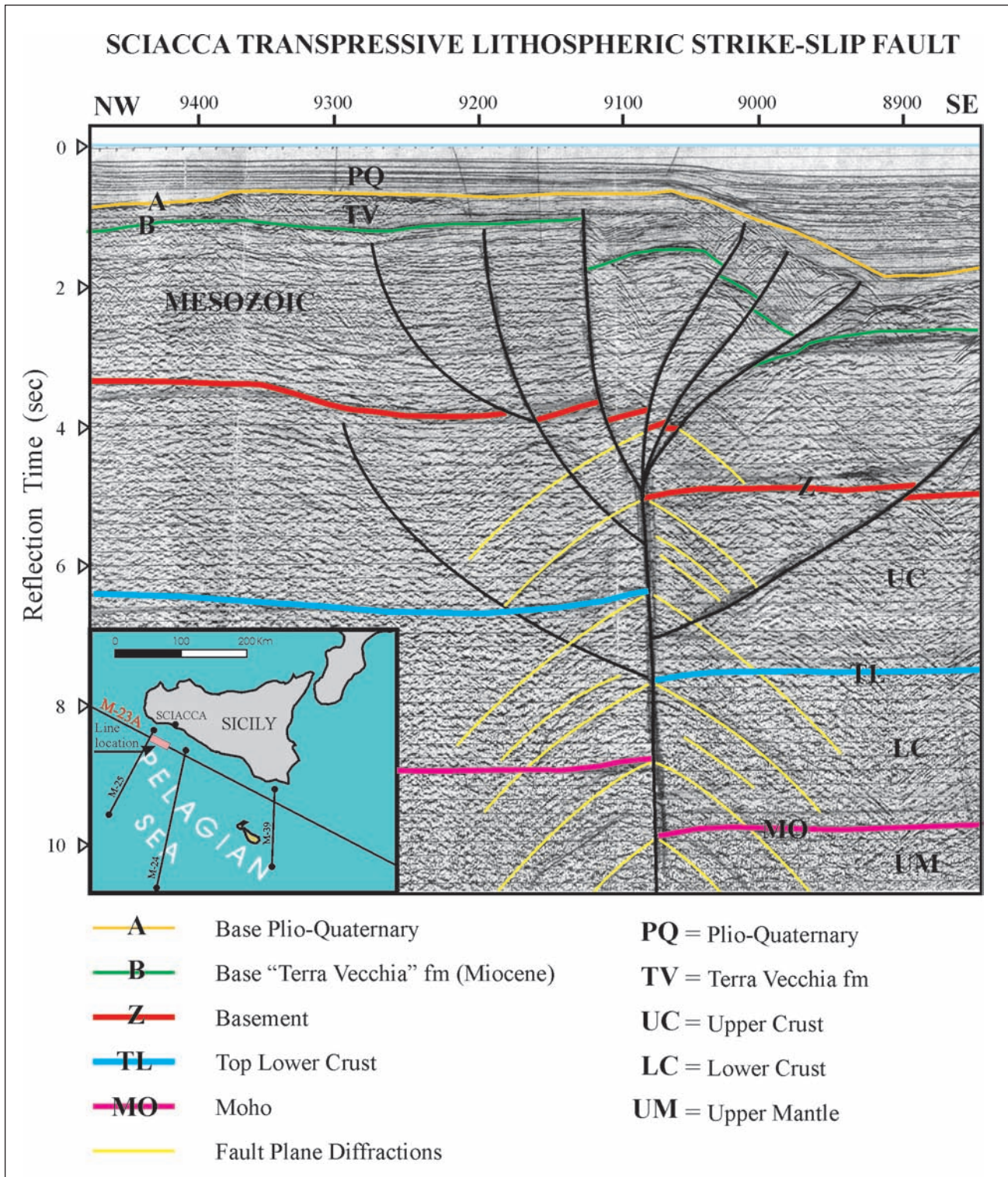


Fig. 9 - Part of CROP Seismic section M-23A, crossing the Sciacca transpressive lithospheric strike-slip fault in off-shore SW Sicily. This flower feature is generated by a left NNE-SSW trending transcurrent fault, as antithetic element perpendicular to the main NW-SE right transcurrent system of the Pelagian Sea. It may be confused for a thrust structure on the sedimentary cover (CATALANO *et alii*, 2000).

- Porzione della linea CROP M-23A, che attraversa la faglia transpressiva litosferica di Sciacca settore marino a SW della Sicilia. Questa struttura a fiore è generata da una faglia trascorrente sinistra, orientata NNE-SSW, che rappresenta un elemento antitetico rispetto al sistema principale trascorrente NW-SE ubicato nel canale di Sicilia. Può essere confusa con un sovrascorrimento nella soportura sedimentaria (CATALANO *et alii*, 2000).

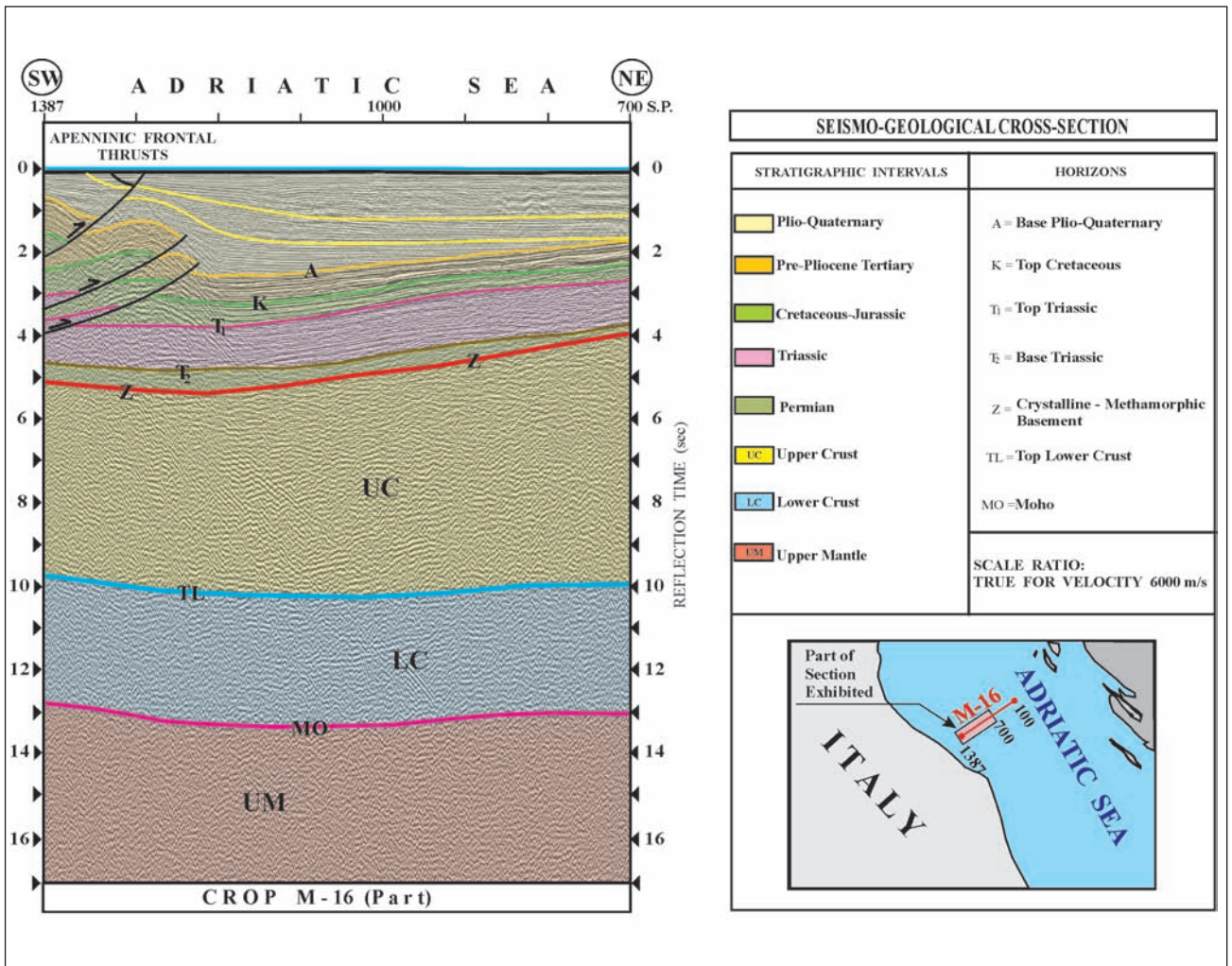


Fig. 10 - South-western part of the interpreted CROP MARE M-16 section, showing the frontal thrust of the Northern Apennines and the structural-stratigraphic setting of the entire crust. Extensional faults of the Lower-Middle Triassic (transpressive) rifting stage, evident on large scale section, are not plotted in this reduced figure, where picking of horizons "T2", "Z", "TL" and "MO" is smoothed. This section has been processed by the Exploration Geophysics Group of the University of Trieste.

- Porzione sud-occidentale, interpretata, della linea CROP MARE M-16 che mostra il sovrascorrimento frontale dell'Appennino settentrionale e l'assetto stratigrafico-strutturale dell'intera crosta. Faglie estensionali della fase di rifting (transpressiva) del Trias inferiore-medio, evidenti in sezioni a grande scala, non sono rappresentate in questa figura ridotta dove le tracce degli orizzonti interpretati "T2", "Z", "TL" e "MO" a cavallo delle faglie sono state lisciate. Questa sezione è stata processata dal Gruppo di Geofisica d'Esplorazione dell'Università di Trieste.

M-18, horizons TL (top lower crust) and MO (Moho) are much more clearly identified than on M-13. The example of the interpreted CROP MARE section of the Central Adriatic (M-15, in part), in the Pescara basin (fig. 11), is more detailed than figure 10, because the time analysis of the Dinaric and Apenninic deformational events, both represented in figure 11, requires a thinner horizon control. It is evident from figure

11 that the Apennine tectonics was very active in the Lower Pliocene, while the frontal Dinaric activity is older.

The apparently simple frontal thrusts of the Dinarides shown in figure 11 effectively represent prominent transpressive deformations of right polarity, which are typical not only of the tectonics of this zone, but of the entire eastern part of the Middle Adriatic.

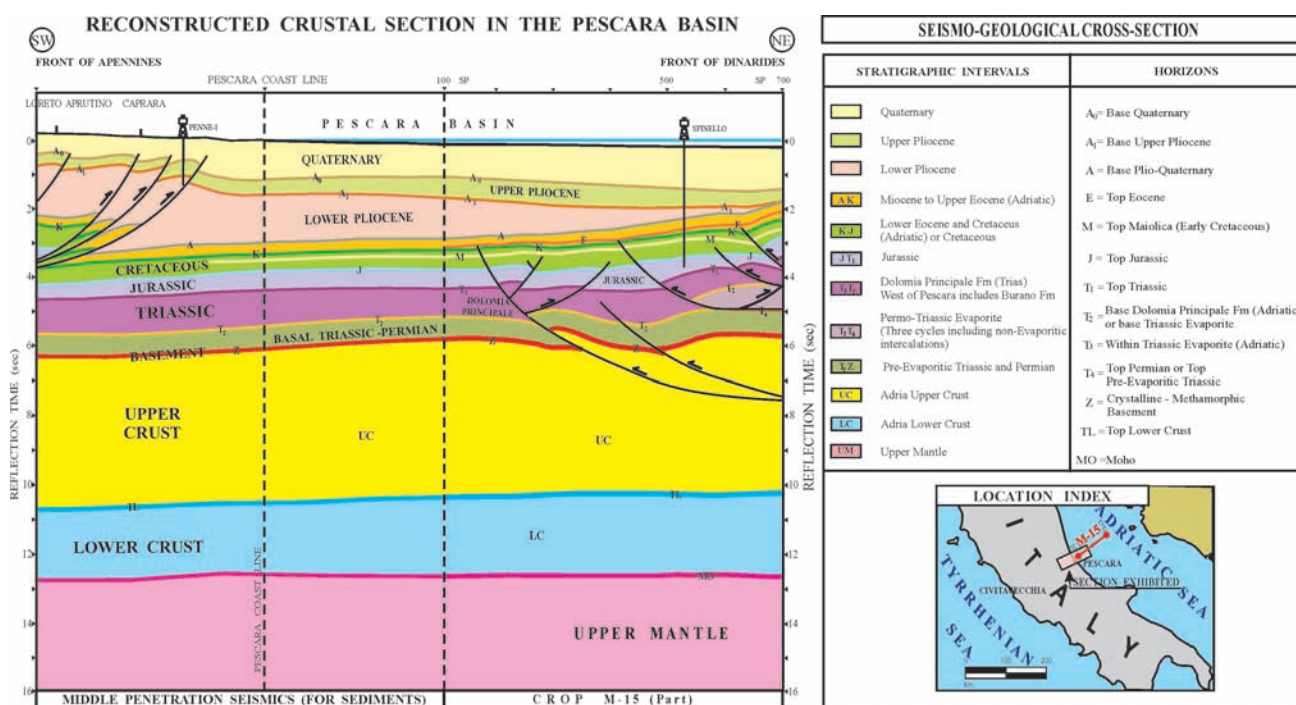


Fig. 11 - Reconstructed crustal section of the Pescara Basin area and opposite thrust fronts of the Apennines and Dinaric systems. From CROP MARE M-15 (part) and other seismic sections for the sedimentary crust, and from CROP data extrapolation for the upper and lower crust and upper mantle.

- Ricostruzione della sezione crostale del bacino di Pescara e sovrascorrimenti frontali opposti degli Appennini e delle Dinaridi. Da parte della linea CROP MARE M-15 e da altre sezioni sismiche per le coperture sedimentarie e dall'extrapolazione di altri dati CROP per la crosta inferiore e superiore e per il mantello superiore.

REFERENCES

- CATALANO R., FRANCHINO A., MERLINI S. & SULLI A. (2000) - Central western Sicily structural setting interpreted from seismic reflection profiles. *Mem. Soc. Geol. It.*, **55**: 5-16.
- FINETTI I., MORELLI C. & ZARUDZKI E. (1970) - Reflection seismic study of the Tyrrhenian Sea. *Boll. Geof. Teor. Appl.*, **12**: 311-345.
- FINETTI I. & MORELLI C. (1972) - Wide scale digital seismic exploration of the Mediterranean Sea. *Boll. Geof. Teor. Appl.*, **14**: 291-342.
- FINETTI I. & MORELLI C. (1973) - Geophysical exploration of the Mediterranean Sea. *Boll. Geof. Teor. Appl.*, **15**: 263-341.
- FINETTI I. & MORELLI C. (1974) - Esplorazione geofisica dell'area mediterranea circostante il Blocco Sardo-Corso. In: *Paleogeografia del Terziario Sardo nell'ambito del Mediterraneo Occidentale*; "Rendic. Sem. Fac. Scienze, Università di Cagliari".
- FINETTI I. (1976) - Mediterranean Ridge: A young submerged chain associated with the Hellenic Arc. *Boll. Geof. Teor. Appl.*, **18**: 31-62.
- FINETTI I. (1982) - Structure, stratigraphy and evolution of Central Mediterranean. *Boll. Geof. Teor. Appl.*, **24**: 247-426.
- FINETTI I. (1984) - Geophysical study of the Sicily Channel Rift Zone. *Boll. Geof. Teor. Appl.*, **26**: 3-28.
- FINETTI I. & DEL BEN A. (1986) - Geophysical study of the Tyrrhenian opening. *Boll. Geof. Teor. Appl.*, **28** (110): 75-156.
- FINETTI I. & DEL BEN A. (2000) - Ionian opening, crustal stratigraphy and tectono-dynamics of the Pelagian Sea region from new CROP seismic data. *Proceedings of the 2nd International Symposium of Geology of NW Libya, Tripoli, 9-15 November 2000*, in press.
- FINETTI I., LENTINI F., CARBONE S., CATALANO S. & DEL BEN A. (1996) - Il sistema Appenninico Meridionale-Arco Calabro-Sicilia nel Mediterraneo Centrale: studio geofisico - geologica. *Boll. Soc. Geol. It.*, **115**: 529-559.
- FINETTI I., BOCCALETTI M., BONINI M., DEL BEN A., GELETTI R., PIPAN M. & SANI F. (2001) - New crustal section based on CROP seismic data across the North Tyrrhenian - Northern Apennines - Adriatic Sea. *Tectonophysics*, **343**: 135-163.
- FINETTI I., LENTINI F., CARBONE S., DEL BEN A. & GUARNIERI P. (in press) - Tectono-stratigraphic setting of Sicily and its Tyrrhenian margin, from new CROP seismic data. In: I. FINETTI (Ed.): "CROP, Deep Seismic Exploration of the Mediterranean Region", Elsevier Science.
- QUICK J. E., SINIGOI S., NEGRINI L., DEMARCHI G. & MAYER A. (1992) - Synmagmatic deformation in the underplated igneous complex of the Ivrea-Verbanò zone. *Geology*, **20**: 613-616.

- ROURE F., BERGERAT F., DAMOTTE B., MUGNIER J.L., & POLINO R. (Eds.) (1996) - *The ECORS-CROP Alpine seismic traverse*. Mém. Soc. Géol. Fr., **170**: 113 pp.
- SERRI G., INNOCENTI F. & MANETTI P. (1993) - *Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene - Quaternary magmatism of central Italy*. Tectonophysics, **223**: 117-147.
- STAMPFLI G. & MOSAR J. (1999) - *The making and becoming of Apulia*. Special Volume, 3rd Workshop on Alpine Geological Studies. Reprinted from: Mem. Sc. Geol., **51** (1): 141-154.
- STAMPFLI G. (2000) - *Tethyan oceans*. In: BOZKURT E., WINCHES-TER J.A. & PIPER J.D.A., (Eds.): "*Tectonics and Magmatism in Turkey and the Surrounding Area*". Geol. Soc. London, Spec. Publ., **173**: 1-23.
- VOSHAGE H., HOFMANN A. W., MAZZUCHELLI M., RIVALENTI G., SINIGOI S., RACZEK I. & DEMARCHI, G. (1990) - *Isotopic evidence from the Ivrea Zone for a hybrid lower crust formed by magmatic underplating*. Nature, **347** (6295): 731-736.