BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXVI, N. 141-144 - MARCH-DECEMBER 1994

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CRUSTAL STRUCTURES OF THE LIGURIAN, TYRRHENIAN AND IONIAN SEAS AND ADJACENT ONSHORE AREAS INTERPRETED FROM WIDE-ANGLE SEISMIC PROFILES

Abstract. A review of the results obtained from the Deep Seismic Soundings carried out in the Italian Seas and adjacent onshore areas has been attempted with the aim of producing a general characterization and location of the different crustal typologies resulting from the data interpretation. This review will be useful for comparison and integration with the results of the deep vertical seismic profiles in the CropMare 91 project. Results are represented by crustal sections and a Moho depth contour map which outlines the following types: 1) a European continental crust under Corsica and Sardinia; 2) an Afro - Adriatic continental crust generally dipping in the direction of the Ligurian and Tyrrhenian seas; 3) an oceanic crust in the Provençal Basin and central Tyrrhenian sea; 4) an anomalous relatively thin crust which can be differentiated into Ligurian, Tuscan and peri-Tyrrhenian typologies, in places superimposed on the Afro-Adriatic crust.

INTRODUCTION

The wide-angle seismic profiles (D.S.S.) carried out in Italy cover most of the peninsula and adjacent seas in varying detail. Most of the profiles where taken with recording stations on land, utilizing shots offshore and onshore. Signals from a series of closely-spaced shots in the sea, along several sets of directions, were recorded at land stations. In a few cases, recording stations on the sea bottom (O.B.S.) were used. Depending on the position and density of the seismic profiles, the quality of the information is influenced by the technique employed. Good detail was obtained in the coastal belt where closely-spaced shots in the sea were used. This technique provides a series of reciprocal travel-time curves: one series is for each onshore recording station, which can be related to all the shots offshore; the other series is for each shot offshore, which can be related to the whole series of recording stations onshore. This technique was used in the following areas: along the Ligurian coast, between Corsica and Tuscany, in the profile between Gargano and Pantelleria, and in the profiles which cross-cut Calabria. Direct structural investigations in the marine areas were carried out only where O.B.S. were utilized, i.e., in a few profiles of the Ligurian Sea, the Tyrrhenian and the western Ionian Sea.

The results thus obtained have been the subject of several publications, internal reports, and oral presentations at congresses, as can be seen in the bibliography.

The present work consists of a review of all the data pertaining to the Italian seas and adjacent areas, where the deep-reflection seismic profiles of the Crop-Mare 91 project have been planned. Many crustal cross-sections have been reconstructed on the basis of the available interpretations, and after some re-evaluation, with a graphic representation of the different crustal units. A synthesis of all the data allowed us to draw up a Moho-depth contour map, distinguishing the various crustal types.

Manuscript received, December 12, 1992; accepted, September 10, 1993.

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CRUSTAL SECTIONS

Fig. 1 shows the locations of the reconstructed crustal sections. They regularly cross-cut the Italian seas and onshore areas, with the exception of the Adriatic Sea, which is not considered and where data are scarce. Some sections were extended landwards to provide a more complete representation of the crustal structures and their relationships. In the sections, the followings features are shown: velocity isolines and/or the traces of the discontinuity surfaces between strata characterized by different velocity, and the values of P-wave velocity in km/s. For a better representation of the results, crustal structures characterized by diverse velocity ranges have been shaded differently:

- the shallower layers, with velocity below 6.0 km/s, are blank;
- light dotted areas indicate layers with velocity values ranging from 6.0 to 6.5 km/s (upper crust);
- medium dotted areas indicate layers with velocity values ranging from 6.5 to 7.5 km/s (lower crust);
- heavy dotted areas indicate upper mantle layers, with velocity values over 7.5 km/s.
- dashed lines indicate velocity inversions.

Section A-A (Fig. 2), N-S trending, coincides with the European Geotraverse. About 900 km long, it begins in the Po Plain and, after crossing the Apennines, the Ligurian Sea, Corsica and Sardinia, ends in the Sardinian Channel. Many detailed D.S.S. profiles cover this section. In particular, land shots (EGT '86 in the Po Plain; EGT '83 in the Northern Apennines), as well as shots in the sea with a charge of over 700 kg in the Ligurian Sea, N of Corsica, between Corsica and Sardinia and in the Sardinian Channel (EGT '83, '85 and '86), and closely spaced shots in the sea (Ligurian Sea and Sardinian Channel) were carried out. Onshore recording stations were located in the Po Plain, in the Northern Apennines, and in Corsica and Sardinia, while O.B.S. were utilized in the Ligurian Sea and in the Sardinian Channel. Some transverse profiles were done in Corsica ('74 and '78) and Sardinia (1982).

To reconstruct the crustal section shown, the interpretation by Egger et al. (1988) was used. In the northernmost part (Apennines and Po Plain), the interpretation by Buness et al. (1990) was also used. In the northern part of the crustal section, the transition from the Adriatic plate crustal type to that of the Ligurian one is evidenced under the Apennines. The bottom of the Adriatic crust can be observed at a depth of about 30 km at the axis of the Po Plain, dipping southward down to a depth of about 45-50 km. Under the Ligurian coast, it probably reaches a depth of about 55 km. The section shows another, shallow crust-mantle discontinuity at depths between 22 and 25 km under the Apennines. This discontinuity joins with the bottom of the Ligurian Sea crust, the minimum depth of which (17 km) is located halfway between Liguria and Corsica. Under the Apennines, the section shows the subduction of the Adriatic crust below the Ligurian. The extent of the subduction suggests a crustal shortening much greater than that hypothesized on the basis of Neogenic deformations (Giese, 1990).

Southwards, the crust becomes thicker and reaches 33 km under Corsica and 32 km under Sardinia, and has a typical continental structure. Further to the South, the crust thins again to about 19 km under the Sardinian Channel. The velocity values of the upper mantle are low under the Ligurian Sea and Corsica (from 7.5 to 7.7 km/s), but increase to normal values to the south. Under Corsica and in the northern part of Sardinia, a discontinuity at a depth of 15-20 km, marked by an abrupt change in velocity from 6.3 to 6.6 km/s, can be observed. Mean crustal velocity is generally lower in southern Sardinia. Finally, the transition from Corsican and Sardinian continental crust to the Ligurian Sea and Sardinian Channel thin crust occurs without abrupt changes.

As for thickness and average velocity values, the crustal structure of the two islands was not strongly affected by their rotation during the opening of the Provençal Basin. However, this rotation may be responsible for the relatively low velocity recorded in the upper mantle.

Section B-B (Fig. 3), SW-NE trending, cross-cuts the Ligurian Sea north of Corsica and the Apennines between Viareggio and Bologna. Available D.S.S. data pertain to a series of

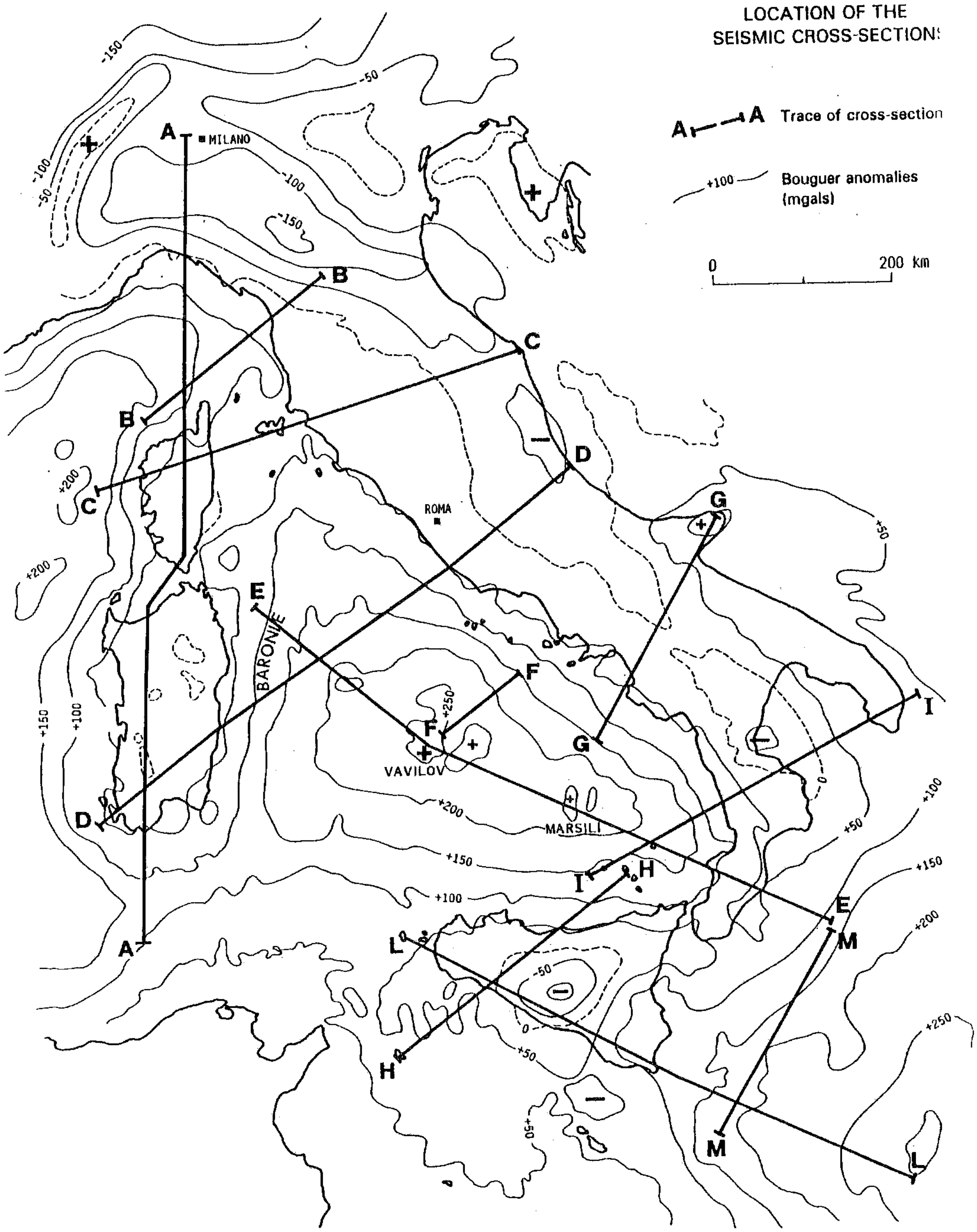

Fig. 1 — Traces of the crustal cross-sections derived from the D.S.S. seismic profiles.

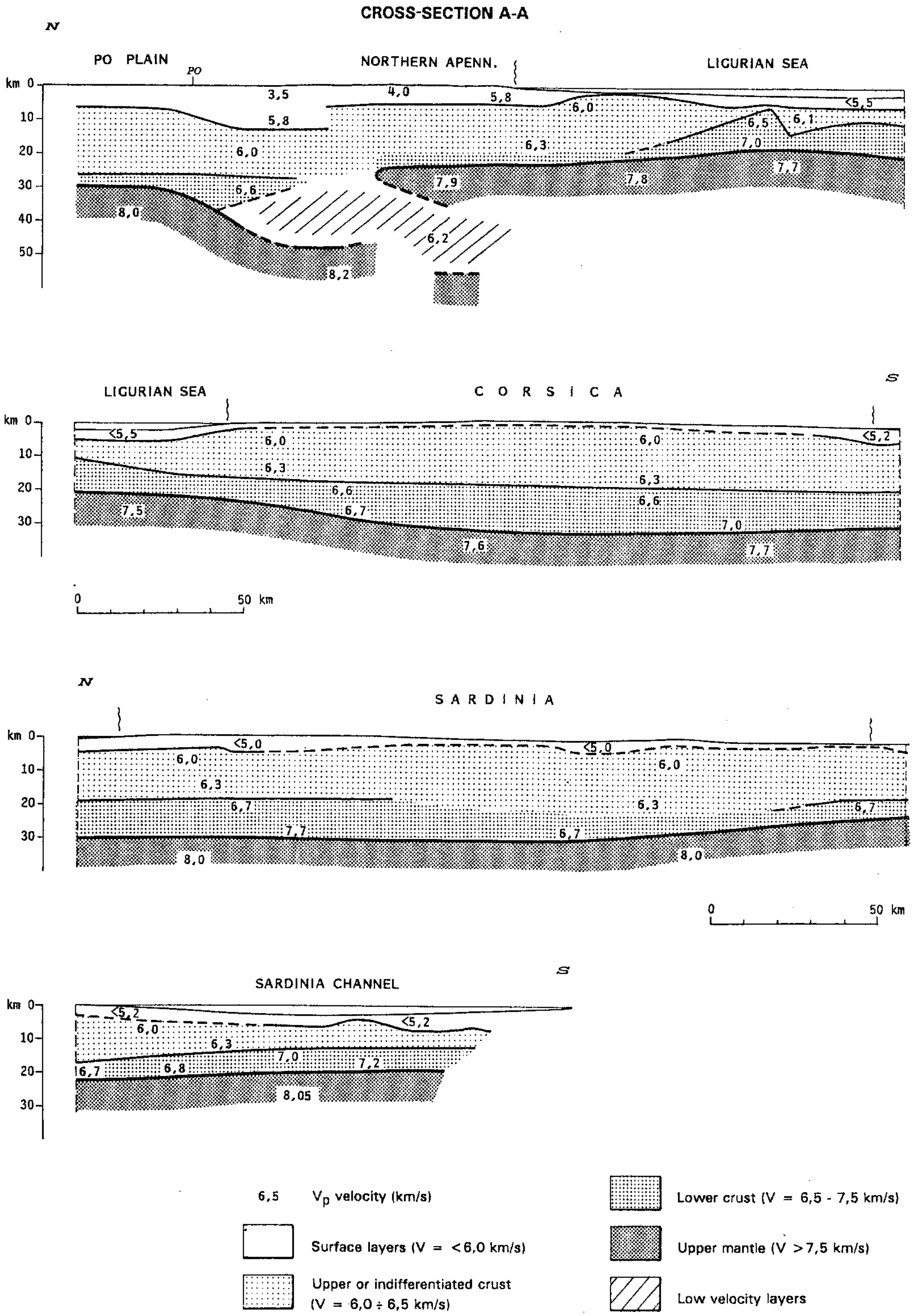

Fig. 2 — Crustal cross-section from the Po Plain to the Sardinian Channel through the Northern Apennines, Corsica and Sardinia.

closely-spaced shots in the sea recorded by onshore stations. However, there is a gap of about 100 km between the location of the shot point closest to the shoreline and the first onshore station. As a consequence, only qualitative data about crustal structures can be drawn, but enough to follow a refracting horizon (Pn phase) for a distance of about 80 km in the Ligurian Sea and about 50 km under the Apennines. The velocity of this discontinuity is about 7.5 km/s, and the depth of this gently NE dipping surface is about 20 km in the first tract and 20-25 km under the Apennines. A deeper discontinuity, dipping to the NE, can be recognized off the coast, with velocity of 8.0-8.2 km/s, at a depth of 45-50 km (Colombi et al., 1977).

More data are available for **Section C-C** (Fig. 4) and the interpretation is thus better constrained. Data have been obtained both from a series of closely-spaced shots in the sea W of Corsica and between Corsica and Elba, and from onshore shots located near Grosseto, Perugia and Ancona. Land-based recording stations were located in Corsica, Elba and between Tuscany and the Marches. The section was reconstructed using interpretations by Hirn et al. (1977), Letz et al. (1977) and Wigger (1984).

The following different crustal types were recognized:

- oceanic crust in the Provençal Basin W of Corsica, with minimum thickness of about 17 km and mean velocity of 6.1 km/s overlying upper mantle with velocity of 7.7 km/s;

- European continental crust under Corsica, with the characteristics described in section A-A;

- anomalous thin crust which starts at Elba and extends under the whole of Tuscany. This crust is characterized by thicknesses between 22.5 and 27.5 km, the presence of layers with velocity reversals at the base of the crust, and upper mantle with relatively low velocity;

- continental crust of the Adriatic Plate, about 30 to 35 km thick, between Perugia and Ancona.

Between Elba and Tuscany a deep discontinuity is observed deepening to the E from 35 km depth under Elba to 60 km under the Tuscan coast. It is comparable to the deep discontinuity in the section B-B (see Fig. 3) and could represent an extention to the E of the bottom of the Corsica crust. The available seismic data are insufficient to provide good detail of the transition between the Adriatic continental crust and the anomalously thin Tuscan crust. However, a variation in thickness of about 10 km can be observed under Perugia. Although the available data do not record any deep discontinuity under Tuscany to be correlated with the bottom of the Adriatic crust, the hypothesis of westward subduction of the Adriatic crust under the thin Tuscan one cannot be ruled out.

Section D-D (Fig. 5) covers the Sardinia (C.S. Antioco-Arbatax) to Pescara tract, crossing the Tyrrhenian Sea and the Apennines. This tract was only partially explored: some data are available only in the coastal belt of Sardinia, in the Thyrrhenian (from two OBS), and in the zone between Latina and Pescara (one reversed profile). The section was reconstructed on the basis of the interpretations by Scarascia (1980), Nicolich (1981) and the Italian Explosion Seismology Group (1982).

The southwestern part of the section shows a gradual transition from continental crust under Sardinia to oceanic crust towards both the western Mediterranean and the Tyrrhenian. Minimum crustal thickness in the Tyrrhenian is about 17 km, where sections D-D and E-E cross. Towards the Italian coast, the thickness gradually increases up to 26 km E of Latina. Thicknesses of about 30 km, typical of the Adriatic crust, can be observed W of Pescara. Between Latina and Pescara, the same abrupt deepening of the Moho observed in section C-C under Perugia occurs.

Section E-E (Fig. 6), NW-SE trending, starts at the Bocche di Bonifacio, crosses the Tyrrhenian Sea (Baronie, Vavilov, Marsili), Calabria (C. Vaticano, P. Stilo) and ends in the Ionian Sea. The Tyrrhenian tract was explored with a series of O.B.S. and closely-spaced shots in the sea. In Calabria and in the coastal belts, closely spaced shots in the Tyrrhenian and Ionian seas were recorded by stations located inland. Reconstruction of the section is based on the interpretations by Steinmetz et al. (1983) for the Tyrrhenian, by the Italian Explosion Seismology Group (1980) for Calabria and coastal belts, and by Linari (1981) for the Ionian Sea. In the Tyrrhenian, it was possible to follow continuously the Moho trend and depths by

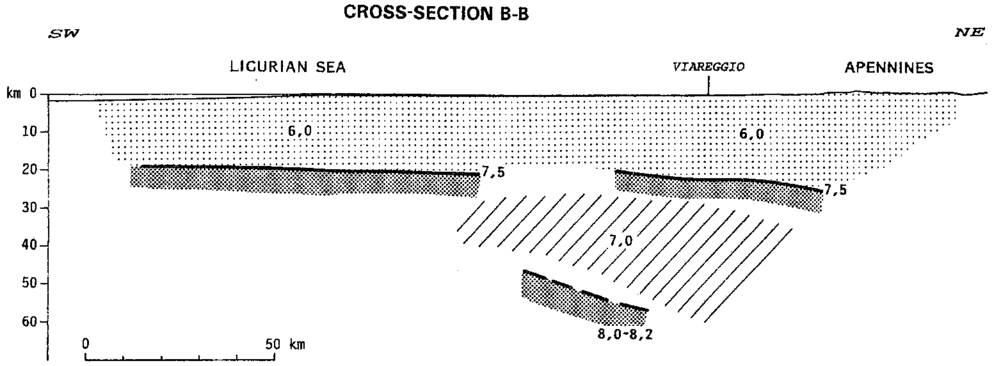

Fig. 3 — Crustal cross-section from the Ligurian Sea to the Emilian Apennines (see Fig. 2 for symbols).

hypothesizing a mean crustal velocity of 6.0 km/s, and by correlating Pn phases. The mean velocity of the upper mantle is about 8 km/s. The trend of the crust-mantle discontinuity in the Tyrrhenian Sea shows a Moho characterized by two zones of minimum depths, one of which is at a depth of 9 km below the Vavilov basin. The other is at a depth of 11 km below the Marsili basin. The two areas of maximum ascent of the Moho correspond to two gravity maxima in the Tyrrhenian, with values over 250 mgal. Between these areas, there is a broad subsided zone where the Moho is over 20 km deep. This phenomenon supports the hypothesis that the opening of the Tyrrhenian ocean started from two distinct centres, the most recent of which is the southeasternmost.

At the NW end, towards Corsica, the section shows a deepening of the Moho down to 29 km, related to the continental structure of the Corsican crust. To the SE, the crust is relatively thin (between 14 and 20 km), both in the southern Tyrrhenian and under Calabria. About 20 km off the Calabrian coast, in the Ionian Sea, the shallower discontinuity (15 km deep) disappears, and a deeper discontinuity (at a depth of over 35 km) is recorded. This latter gradually rises to the SE and reaches a depth of 18 km. In this part of the section, under Calabria and its Ionian coast, there is a situation similar to that described under the Northern Apennines and the Ligurian Sea, where the results indicate the N to S subduction of the Po Plain crust below the Ligurian crust (section A-A). In this case, subduction of the African crust under the thin Calabrian crust from the SE to the NW can be hypothesized. It should be noted that off the Calabrian coast, in the Ionian Sea, there is a zone characterized by an anomalously low crustal velocity (5.8 km/s), corresponding to an abrupt thickening.

Section F-F (Fig. 7) was redrawn after Nicolich (1982). Data come from O.B.S. and closely-spaced shots in the sea along a distance of about 100 km between Vavilov volcano and the island of Ischia in the Tyrrhenian Sea. Here the Moho is about 9 km deep at Vavilov and deepens to 15 km at the ENE end of the section, forming an anticlinal structure located about 60 km off Ischia.

Section G-G (Fig. 8) starts from Gargano, crosses the Southern Apennines and Cilento stretching into the Tyrrhenian for about 50 km. The reconstruction of the section was from surveys carried out in 1971 (land stations and closely-spaced shots in the Tyrrhenian Sea) and 1980 (a series of reciprocal profiles carried out on land, both parallel and perpendicular to the Apennines), and on the interpretations of Colombi et al. (1973), Scarascia (1982). A revision of the available data was also done.

The section shows a peri-Tyrrhenian thin crust, extending inland for about 20 km under Cilento, and an Adriatic continental crust, about 25 km thick under Gargano, which dips to the SW down to a depth of about 50 km (under Cilento). A relatively shallow mantle-crust discontinuity and a deeper one can be recognized in a 50 km-wide belt near the coastline. The section also shows the SW dip of the Apulian carbonate platform. Thus, this section evidences

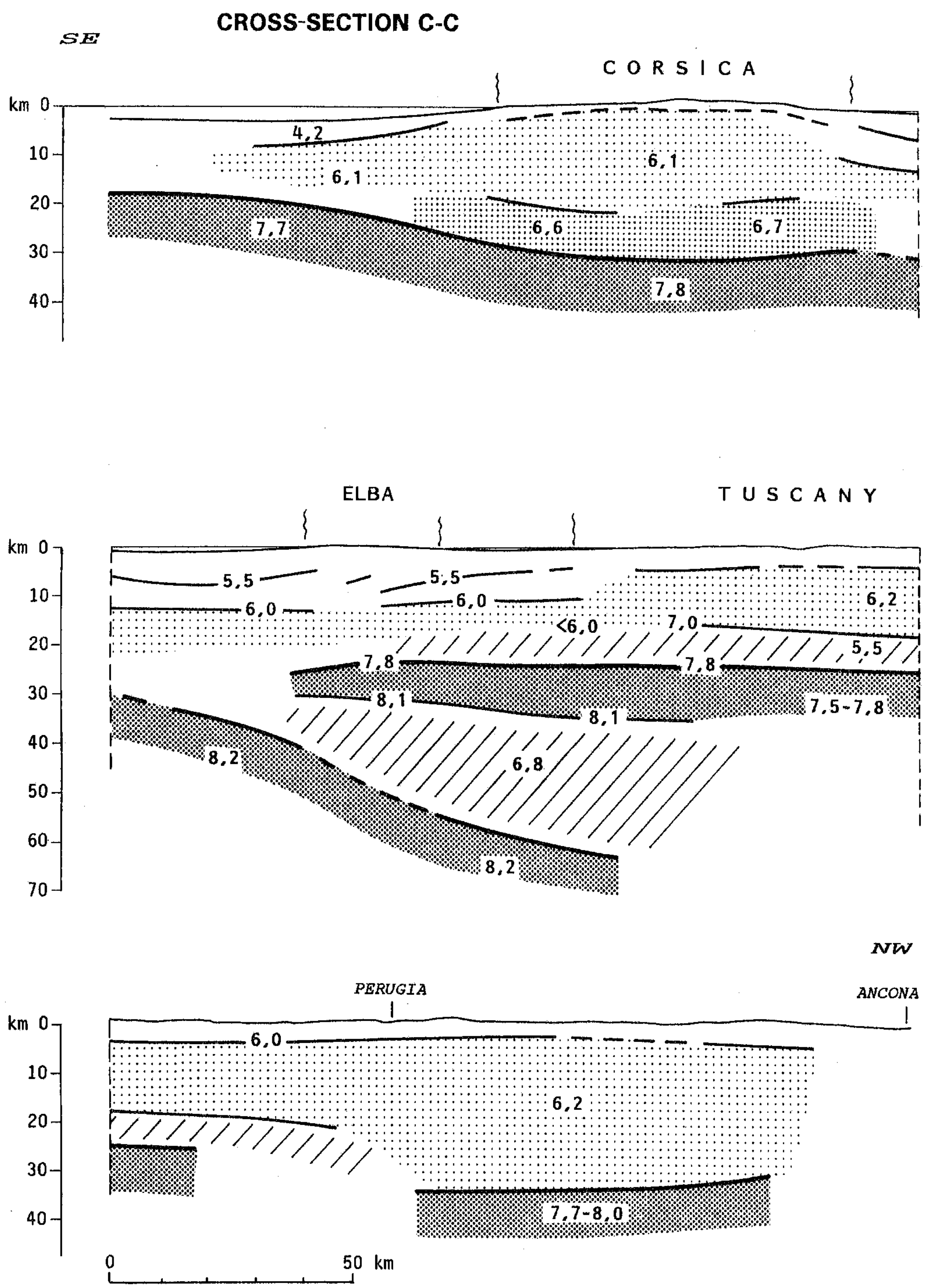

Fig. 4 — Crustal cross-section from Corsica to Tuscany (see Fig. 2 for symbols).

CROSS-SECTION D-D

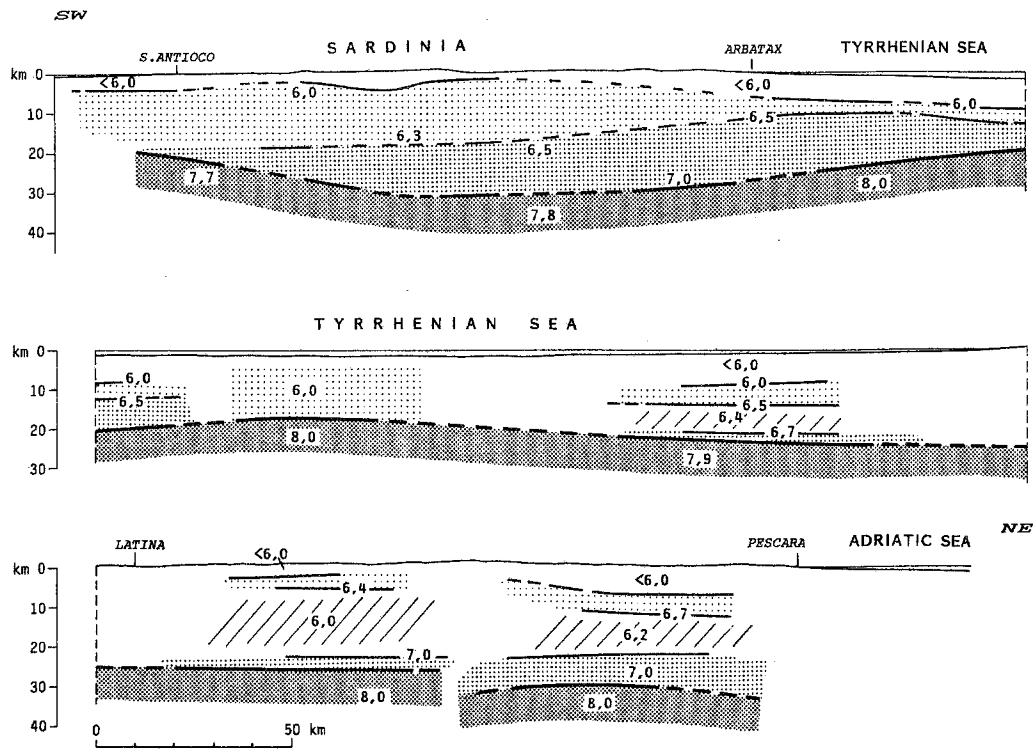

Fig. 5 — Crustal cross-section from Sardinia to Lazio - Abruzzo Apennines across the Tyrrhenian Sea (see Fig. 2 for symbols).

the SW subduction of the Adriatic plate, a phenomenon which was not very clear from the data relative to sections C-C (Elba-Ancona) and D-D (Latina-Pescara) (cfr. Figs. 4 and 5).

Sections H-H and I-I (Fig. 10) are dealt with together because one is the extension of the other. Section H-H starts at Pantelleria, crosses Sicily (Sciacca-Termini Imerese) and ends at Salina (Eolian Islands). Section I-I starts at the Eolian Islands, crosses Calabria and the gulf of Taranto, and ends in the Salento peninsula. Seismic data were obtained from surveys carried out in 1971 (Gargano-Pantelleria profile; Colombi et al., 1973), 1972 (Eolie-P. Salentina profile, Morelli et al., 1975) and 1985 (Sicily, Cosentino et al., 1987). The shots were located in the sea (Sicily Channel, Southern Tyrrhenian, gulf of Taranto and Adriatic Sea) and recorded by land-based stations at Pantelleria, Sicily, the Eolian Islands, Calabria and the Salento peninsula. Section H-H shows a rapid and regular deepening of the bottom of the African crust, from about 20 km under Pantelleria to 40 km under the centre of Sicily. In the southern Tyrrhenian Sea, between Termini Imerese and the Eolian Islands, a thin crust of peri-Tyrrhenian type, from 20 to 25 km thick, can be recognized, as well as a deeper discontinuity correlatable with the bottom of the African crust at a depth of about 40 km. This situation is similar to that seen in section E-E (Fig. 6) under Calabria, which indicates the obduction of the peri-Tyrrhenian crust on the African plate.

Section I-I shows a crustal thickness of about 18 km under the Eolian Islands. Under Calabria, the same situation observed in section E-E (Fig. 6) occurs. In fact, the whole Calabrian part of the section is characterized by a crust-mantle discontinuity at a depth of about 20-25 km, while under the Ionian coastline a deeper discontinuity (at a depth of 40 km) is clear. The latter can be correlated with the bottom of the Salento peninsula continental crust (about 30 km thick).

Section L-L (Fig. 11) is located along the western coast of Sicily, between the Egadi Islands

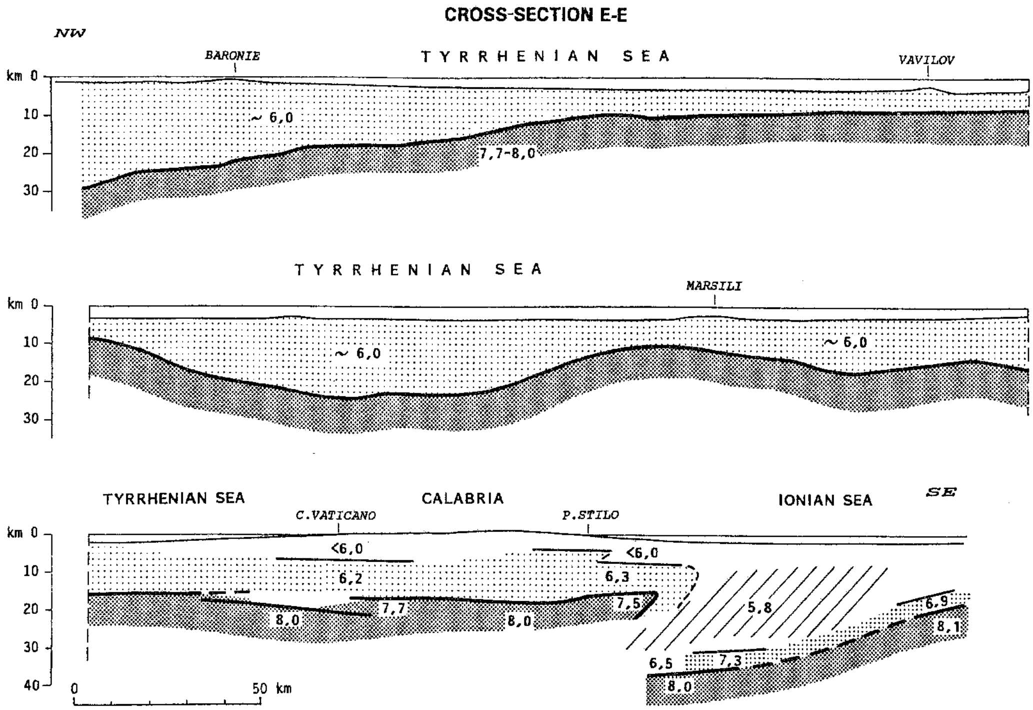

Fig. 6 — Crustal cross-section through the Tyrrhenian Sea, Calabria and Ionian Sea (see Fig. 2 for symbols).

and Capo Passero, and extends to the SE towards the Ionian abyssal plain. The part of the section under Sicily was explored by means of reversed profiles, with shots located in the sea near Egadi, Gela and Capo Passero and recorded by land stations (Cosentino et al., 1987). The sea tract was explored with O.B.S. and closely-spaced shots located in the Ionian Sea (Makris et al., 1986).

Along the SW coast of Sicily, the thickness of the crust varies between 35 and 40 km. The seismic horizon characterized by a velocity of 6.0 km/s deepens down to more than 20 km under the Caltanissetta basin. To the SE, the depth of the Moho rapidly decreases and reaches 17 km at the Malta escarpment. At the SE end of the section, near the Ionian abyssal plain, the depth of the Moho is 12 km. In the part of the section under the Ionian Sea, layers of low-velocity sediments, up to 5 km thick, can be observed.

Section M-M (Fig. 12), located off the Sicilian and Calabrian coasts, runs parallel to them. It was interpreted by Makris et al. (1986). The depth of the Moho is between 18 and 20 km, and the sedimentary cover can be up to 10 km thick.

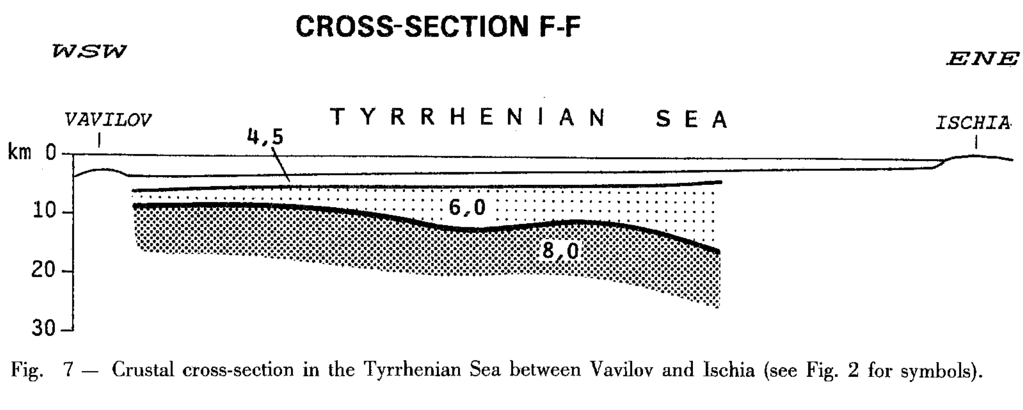

Fig. 7 — Crustal cross-section in the Tyrrhenian Sea between Vavilov and Ischia (see Fig. 2 for symbols).

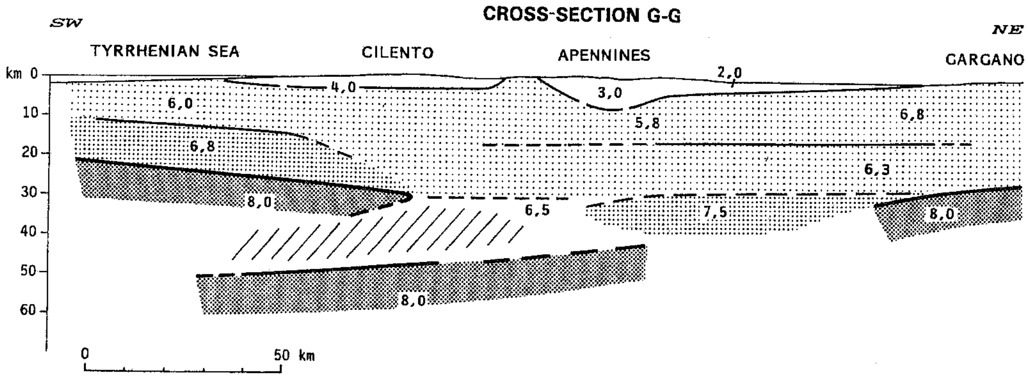

Fig. 8 — Crustal cross-section, Tyrrhenian Sea - Cilento - Gargano (see Fig. 2 for symbols).

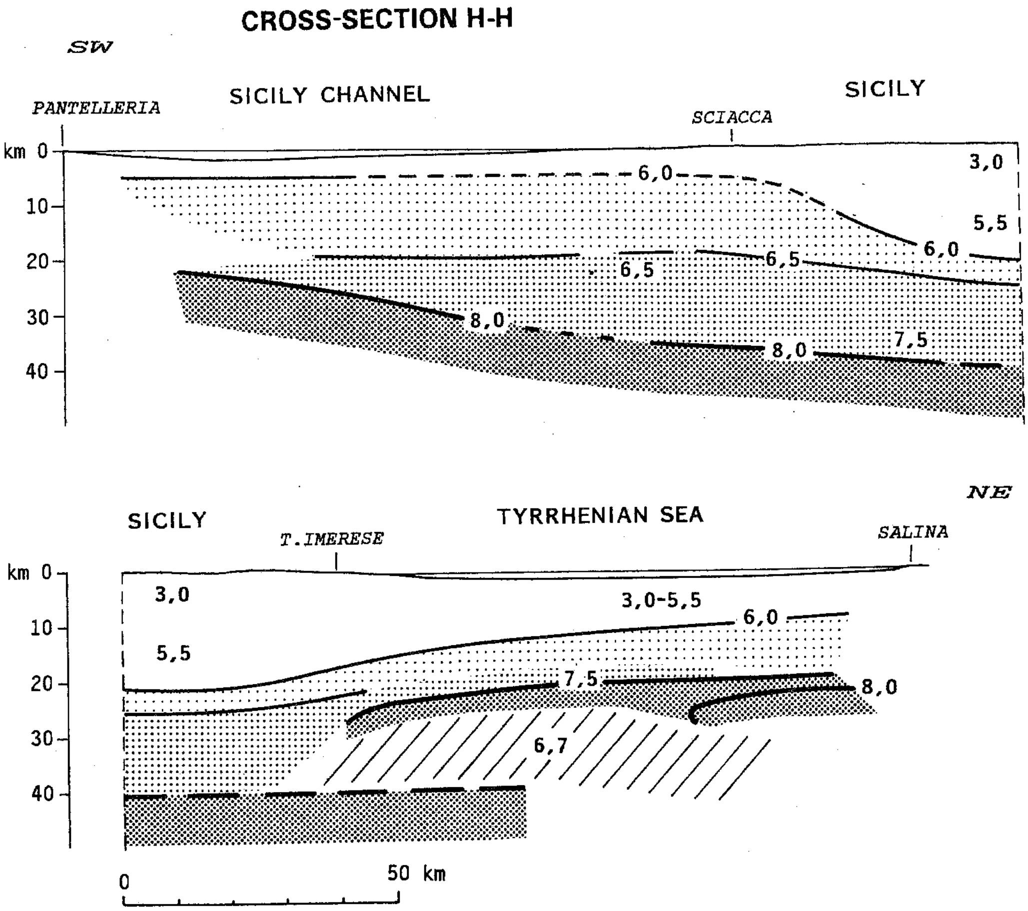

Fig. 9 — Crustal cross-section, Pantelleria - Sicily - Eolian Islands (see Fig. 2 for symbols).

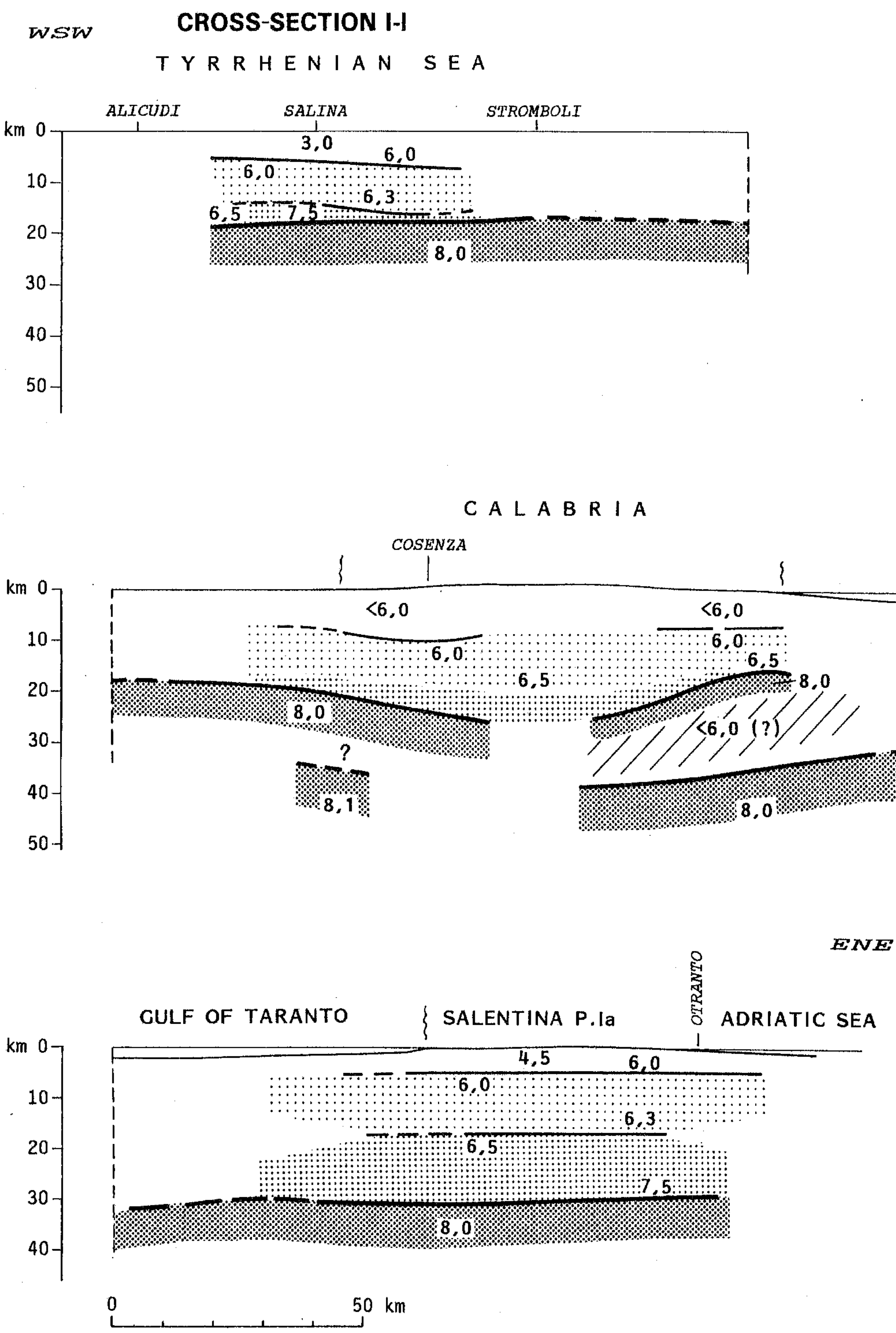

Fig. 10 — Crustal cross-section, Eolian Islands - Calabria - Salento Peninsula (see Fig. 2 for symbols).

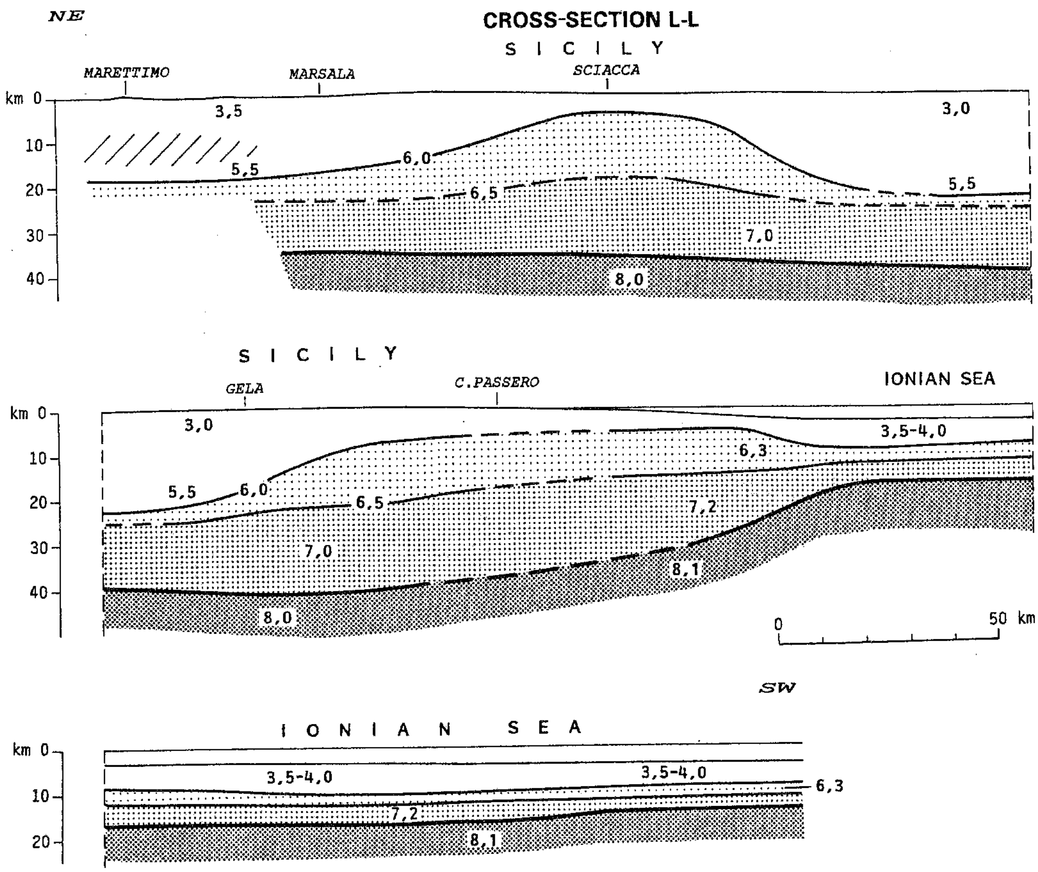

Fig. 11 — Crustal cross-section, Egadi Islands - Passero Cape - Ionian Sea (see Fig. 2 for symbols).

MOHO MAP AND CONCLUSIONS

Fig. 13 shows the Moho isobaths in the area covered by the crustal sections described. The different crust types recognized by interpreting the D.S.S. profiles are indicated by different symbols. The first crust type is the African continental crust (Adriatic plate, Sicilian microplate), which can be observed under the whole Italian peninsula and Sicily. The second crust type is the European continental crust, which is present in the Sardinia-Corsica microplate with a possible extension in depth towards Tuscany. The third type is the thin crust of the oceanic

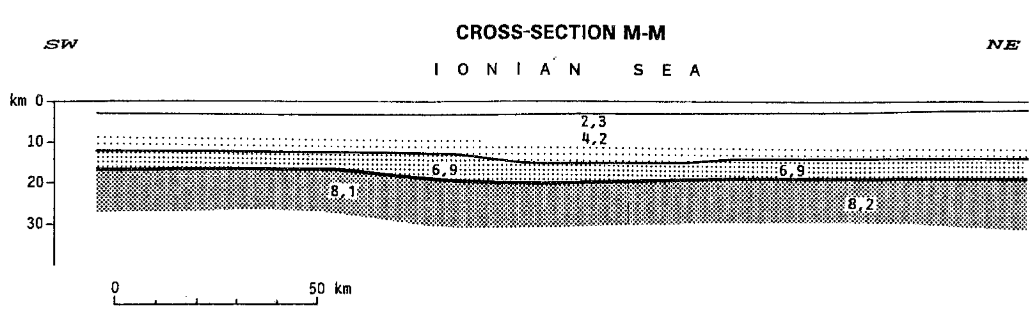

Fig. 12 — Crustal cross-section in the Ionian Sea (see Fig. 2 for symbols).

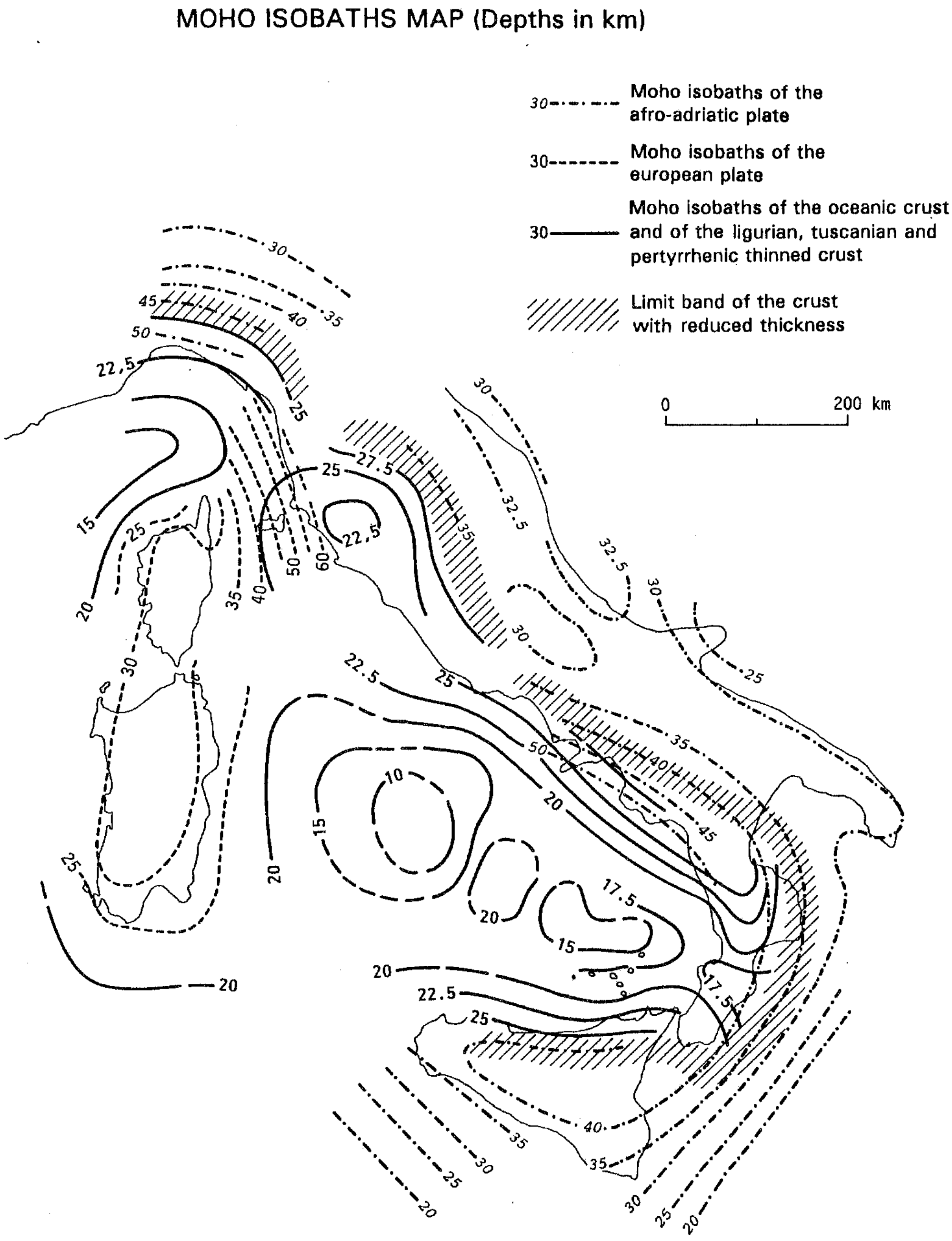

Fig. 13 — Moho - depth contour map.

areas, the anomalous thin crust of the Ligurian and Tuscan regions, and of the peri-Tyrrhenian belt.

This map of the Moho isobaths and crustal types is a useful tool for studying the geodynamic evolution of the area. The first process involved was the opening of the Provençal Basin and the rotation of the Sardinia-Corsica microplate; the second event was the opening of the Tyrrhenian Sea, from two different centres of expansion (Vavilov and Marsili basins) and at different times. This second process brought the Calabrides into their present position by means of an ESE migration of about 300 km, and caused an anticlockwise rotation of the Southern Apennines (Finetti et al., 1986).

The evolution of the area located between Corsica and Liguria is related to the rotation of the Sardinia-Corsica microplate. At present, there is European continental crust under Sardinia and Corsica, and an extension in depth of this crustal type is possible in the direction from Corsica to the Tuscan coasts, as indicated by the deep Moho isobaths plunging to NE. This deepened European crust could represent lithospheric remnants of the eo-mesoalpine subduction. In Liguria and Tuscany, a shallower discontinuity extends onshore; therefore, in these two regions, anomalous thin crustal types, divided into two subtypes with respect to geography and composition, can be recognized. The first subtype is the "Ligurian Crust", which is present under the Northern Apennines and extends to the N for about 30 km off the coastline, with thicknesses ranging from 22 to 25 km. The second subtype, the "Tuscan Crust", recognized under Elba and Tuscany, shows thicknesses from 22 to 27 km and is characterized by low velocity layers at the base (Fig. 4). The low velocity zone may be related to the geothermic regime of the region. From the trend of the Adriatic plate crust between the axis of the Po Plain and the Northern Apennines, it is possible to infer a southward dipping of the Moho, which extends to the coastline under the thin "Ligurian crust". In Tuscany, crustal sections show a sudden change in the depth of the Moho (about 10 km) limiting the extension of the Tuscan crust to the E. However, it is possible that a westward subduction of the Adriatic plate also occurs in this zone, even if D.S.S. data are insufficient to support this hypothesis.

In conclusion, the thin Ligurian and Tuscan crusts may represent a peripheral part of the Adriatic crust which was detached, lifted and thinned during the collision with the European Plate. The western limit of this thinned Adriatic crust may be located W of Elba, and probably extends to the NNW with a trend parallel to the coastline; to the S, no information is available. In the map, the eastern and northern limits of the thinned Adriatic crust are hatched.

Further to the south, the most important geodynamic process was the opening of the Tyrrhenian Sea. The map does not show abrupt changes of crust thickness from Sardinia (continental crust 30 km thick) to the surrounding seas (oceanic crust with thickness of less than 10 km in the Vavilov Basin). On the contrary, the transition from the thin peri-Tyrrhenian crust to the Afro-Adriatic continental crust occurs through the abrupt change in the depth of the Moho and some crustal duplications along the whole coastal belt, which from Latina extends to Calabria and to the northern coast of Sicily. Under the hypothesis of a subduction of the Afro-Adriatic plate, it seems always to be oriented towards the Tyrrhenian, i.e.: to the SW along the coast of Campania and northern Calabria, to the NW under southern Calabria, and to the N along the northern coast of Sicily. Under the coast of Cilento, the bottom of the Adriatic crust can be observed at a depth of 50 km, while the bottom of the Tyrrhenian crust can be recognized at a depth of about 27 km. Thin crust, with thicknesses between 15 and 25 km, characterizes the whole of southern Calabria, while the bottom of the African crust can be found at a depth of 45 km. From Calabria to the SE (Ionian abyssal plain), and from Sicily to the SW (Pantelleria), the isobaths indicate a regular thinning of the African crust, which reaches thicknesses of 12 km near the abyssal plain, and 20 km near Pantelleria.

In conclusion, the opening of the Tyrrhenian Sea formed a belt where the thin peri-Tyrrhenian crust ovrethrusts the Afro-Adriatic continental crust. This belt has its greatest extension under southern Calabria. The NW dipping of the African Moho under Calabria may represent the beginning of the subduction of the African lithospheric slab towards the Tyrrhenian. The limits of the overthrust are indicated by the hatched belt in the map. This belt forms a bow which, starting from the coast near Anzio, heads for the Gulf of Taranto, then follows the eastern coast of Calabria and the northern coast of Sicily.

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