

Seismicity and crustal structure in the Italian region: a new review using a synthesis of DSS results and updated catalogues of earthquakes

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(Received April 11, 2005; accepted July 6, 2005)

ABSTRACT Both historical and instrumental updated catalogues of the earthquakes in the Italian region, are used to compare the location of the epicentres and the focal depth of seismic events with the structure of the Earth crust as determined by the Deep Seismic Soundings (DSS) and according to a published interpretative synthesis. In the past, several attempts were made to do this on the same subject; however, the investigations concerned only some areas of the region, when both the seismic activity and the interpretation of DSS profiles were often based upon inhomogeneous or preliminary data. In this work, we profit from the most recent and complete database of Italian seismicity, to extend the study to the whole peninsula. The comparison confirms that the seismicity occurs more frequently where structural changes are observed by the DSS profiles. The main activity seems to originate in the upper, brittle crust; nevertheless, even the shallow events are particularly concentrated where tectonic features were discovered in the lower crust or at the Moho boundary. The hypocenters tend to deepen where a process of active subduction is occurring. It is believed that the results described herewith could be used as additional elements for the study of seismogenesis.

1. Introduction

The aim of this paper is to compare two main data sets: the structure of the Earth's crust in the Italian region, determined by the Deep Seismic Soundings (DSS) or Wide Angle Reflection-Refraction profiles (WARR) technique and the updated catalogues of the earthquakes.

In the past investigations on the same subject were done only on specific areas and using preliminary interpretations of some DSS profiles as well as earthquake hypocenters of variable accuracy, obtained from different sources [see, e.g., Cassinis *et al.*, (1985); Cassinis and Ranzoni (1987)]. Now, more complete and reliable data are available for both data sets.

Over a period of 30 years, a European group jointly with the Italian CNR (National Research Council of Italy) recorded a network of DSS soundings in Italy and the surrounding seas. Different authors proposed several interpretations for each profile. Field operations were terminated more than 10 years ago due to the lack of funding and to environmental constraints, also because priority was given to new programmes for the creation of deep seismic reflection profiles (CNR - CROP, TRANSALP). However, the processing and interpreting work was continued through new procedures (digitalisation of the old analogically-recorded data, use of

synthetic seismograms, seismic modelling). Thus, updated interpretations of individual cross sections and more detailed maps of the Moho boundary were proposed.

In this paper, we refer to the published synthesis by Cassinis *et al.* (2003). The traces of the interpreted cross-sections described in this paper are shown in the map of Fig. 1, where the regional Bouguer gravity anomalies (after Morelli, 2000) are also plotted.

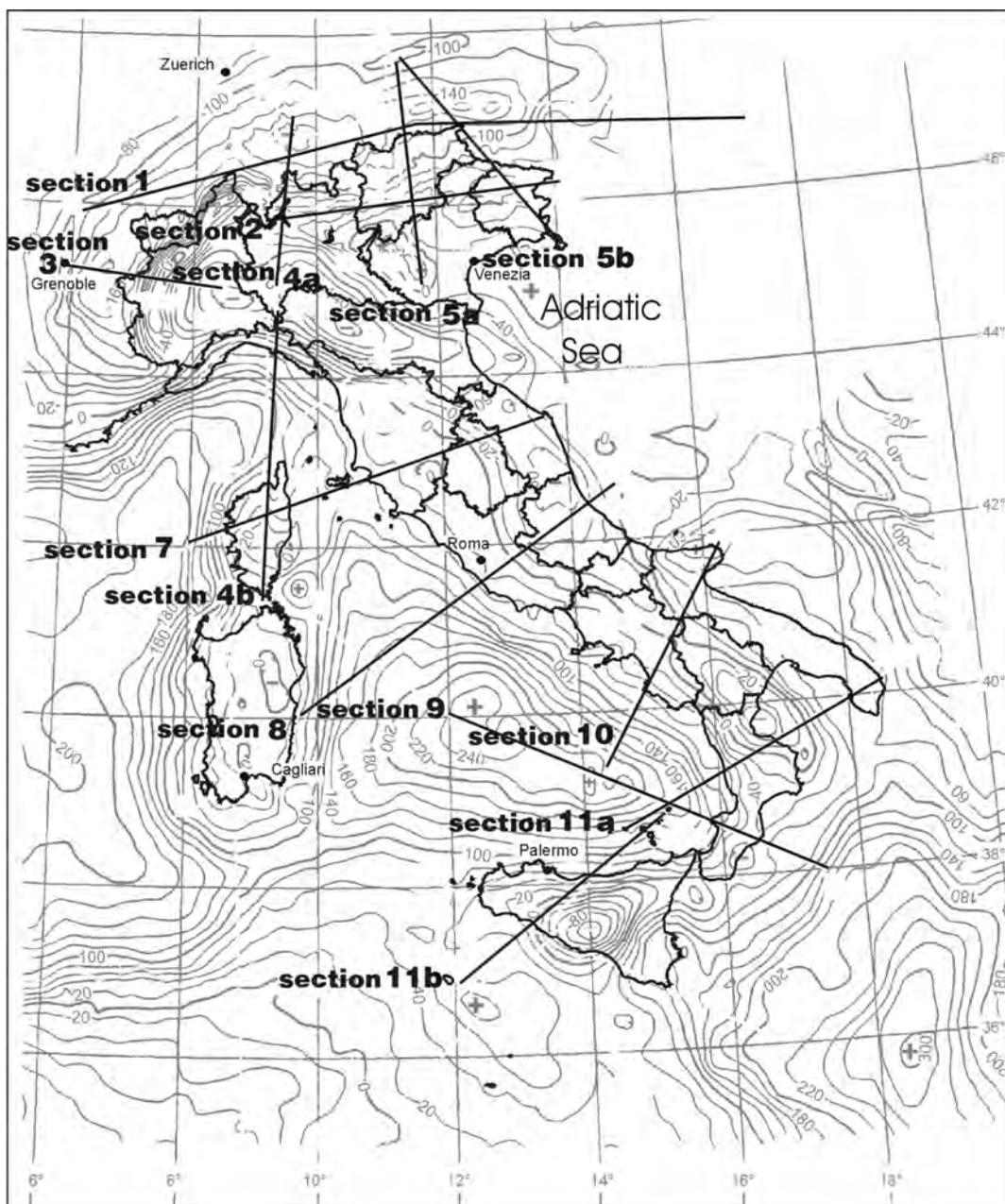


Fig. 1 - Map of the Italian peninsula and surrounding areas with the traces of the interpretative cross-sections described in this paper. The regional Bouguer anomalies (contour interval: 20 mGal) are also plotted after Morelli (2000).

Regarding the second source of data, it is well known that in the last two decades a great effort has been made to improve the knowledge of both historical and recent seismic activity of the Italian peninsula. The technological improvement of seismic instrumentation, the increased availability of computer facilities and the need for a steady seismic monitoring of the country have led not only to an important evolution in seismic networks but also to the compilation of complete and reliable databases. In this paper, the aim of which is to associate seismic activity to mapped structures, we make use of the catalogue published by Camassi and Stucchi (1997) for the historical earthquakes (A.D. 1000 - 1980) and we rely, for the recent seismicity, on the catalogue of the Italian earthquakes (1981-2002) compiled by INGV and discussed in the paper by Chiarabba *et al.* (2005).

2. Crustal domains, structure of the deep crust and distribution of the epicentres

In Fig. 2, the synthesis proposed by Cassinis *et al.* (2003) shows the crustal domains, the Moho depth contours as well as the main tectonic features in the deep crust as interpreted from the DSS data (see the figure captions). Besides the three major domains (European, Adriatic-African and sub oceanic-oceanic) a third, transitional domain is interpreted, characterised by an intermediate type of crust, all along the Ligurian and the Tyrrhenian coasts. A last domain is shown in the north-eastern corner of the map (transition from the European-Alpine domain to the Styrian-Pannonian basins). The transition from the South-Eastern Alps (Adriatic plate) to the Dinarides is left undetermined because of the lack of data east of the Udine-Trieste line.

The main divide along the Alps and the Italian peninsula is marked by a broken black line representing the over-thrusting fronts of the Moho boundary, the European crust being subducted beneath the Adriatic-Padan crust while, along the Perityrrhenian region, the subduction is inverted, the Adriatic crust being subducted beneath the Tyrrhenian.

Along the peninsula the edge of the over-thrusting Moho clearly shows four regions, separated by crustal breaks, respectively corresponding to the Ligurian, North-Central Apennines, Southern Apennines and to the Calabrian-Aeolian arc.

Some criticism was raised on the “excessive” detail shown in this map; we believe that the comparison with other data, such as the seismicity and some deep seismic reflection profiles, clearly confirms the reliability of the interpretation of DSS.

The historical epicentres (for $M_s \geq 4.0$) from Camassi and Stucchi (1997) are plotted on the same map. A general agreement of the earthquakes with the Adriatic subduction along the whole Apenninic range, down to the Aeolian arc, can be seen where the main activity tends to migrate north-westwards with respect to the edge of the Tyrrhenian Moho. In the Alps, the activity concentrates in the south-eastern region (mainly in Friuli) and on the lifted upper mantle block beneath the Euganei Hills, while no historical events are recorded in the Lombardian Alps and the Western Alpine arc, except in the Maritime Alps and in the Ligurian Sea.

Figs. 3, 6 and 9 are enlargements of Fig. 2 where the instrumentally observed epicentres as proposed in Chiarabba *et al.* (2005) are superimposed on the Alps and Northern Apennines (Fig. 3), Central Apennines (Fig. 6) and Calabrian Arc and Sicily (Fig. 9). Three classes of focal depth are distinguished: 0-18, 18-35 and >35 km. This classification is based on a very rough distinction between upper and lower crust and upper mantle. It is worth noting that the events

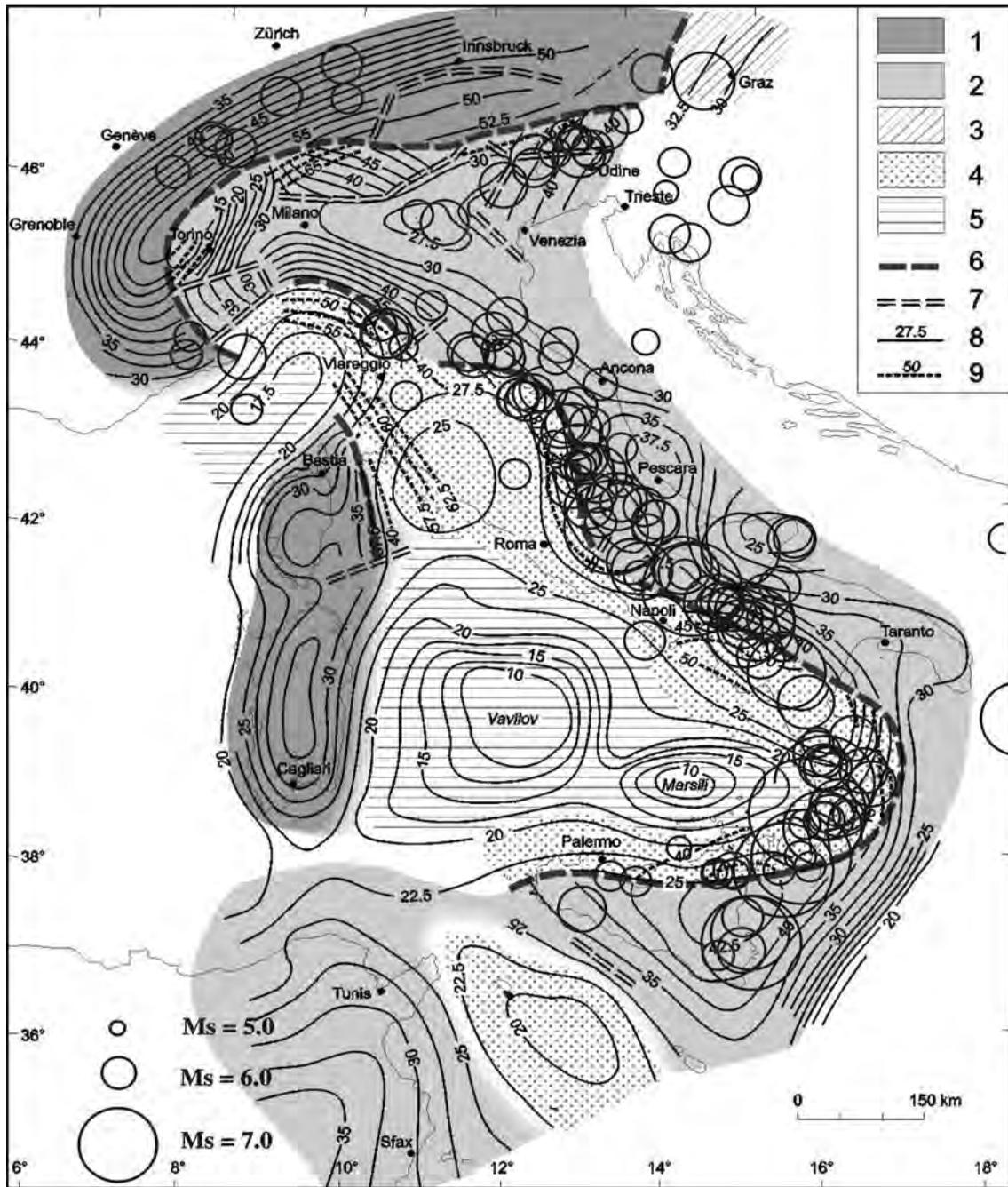


Fig. 2 - Depth contour-lines of the Moho boundary (contour interval 2.5 km) and crustal domains (modified from Cassinis *et al.*, 2003). The historical epicentres with $M_s \geq 4.0$, A.D.1000-1980 (Camassi and Stucchi, 1997) are plotted on the same map .

Explanation of symbols:

Crustal types: 1: European plate; 2: Afro-Adriatic plate; 3: Styrian and Pannonian basins; 4: Ligurian, Tuscan-Perityrrhenian transitional crust [the same ornamentation is used for the Pantelleria rift (Sicily channel)]; 5: oceanic-sub-oceanic crust; 6: Over-thrusting fronts of the Moho boundary: of the Adriatic over the European plate (Alpine range); of the Ligurian, Tuscan, Perityrrhenian transitional crust over the Adriatic-African plate (Apennines range); of the Ligurian-Tuscan over the European (Corsica) plate; 7: fragmentation lines in the upper mantle; 8: Moho depth contour lines (km); 9: Moho depth contour-lines (subducted).

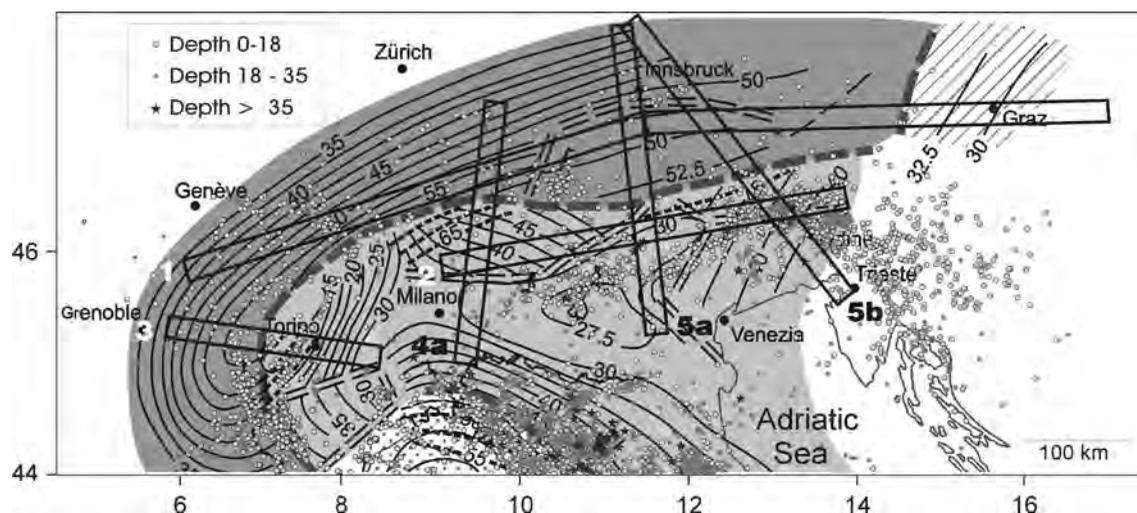


Fig. 3 - Enlargement of Fig. 2 (Alpine range, Po Valley and northern Italy). The instrumentally observed epicentres (1981-2002, $M \geq 1.9$) are plotted after Chiarabba *et al.* (2005). The traces of the cross-sections shown in Figs. 4 and 5 are presented as 20 km-wide strips; the hypocentres falling within each strip are projected on the relevant cross-section (see the following figures). Three classes of depth are distinguished: 0 - 18, 18 - 35 and > 35 km .

shallower than 18 km represent more than 50% of the whole data set. Magnitudes are mainly computed as M_L , except for a few hundred events prior to 1990 and range from 1.9 to 5.8. While looking for a correct relationship between seismic events and seismogenic structures, it is of paramount importance to use data affected by an error less than the estimated size of the structure. Moreover, good additional information is provided by the magnitude of the events. For this reason, the plotted epicenters (about 25,000) are only those whose magnitude and focal depth are determined, the error of positioning being less than ± 3 km. The period of observation (21 years) is relatively short; therefore, fluctuations of the activity in the different areas cannot be avoided. Nevertheless, we preferred to use more reliable data, especially for the focal depth, rather than extend the observation period. For the same reason the information can be poor in some specific regions, where the recording was done by local and transitory seismological networks or where the seismic monitoring has been established only in recent years.

Looking at the three maps a general trend of deepening of the earthquakes can be remarked when moving from north to south; moreover, depths are, as an average, larger along the Adriatic-African margin if compared to the Ligurian-Peri-Tyrrhenian domain. In general, a good correspondence is found among the clusters of the epicentres and the fragmentation lines interpreted in the upper mantle or in the lower crust.

The traces of the interpretative cross-sections that will be described later on are shown as strips, 20-km wide; the hypocentres contained in each strip are projected on each section. We believe that the assumed width is compatible with the accuracy of the epicentral coordinates.

3. Interpretative cross-sections and hypocentres

All the interpretative cross-sections illustrated here are taken from Cassinis *et al.* (2003). The presentation is as much as possible homogeneous for all profiles. The interpretation by the

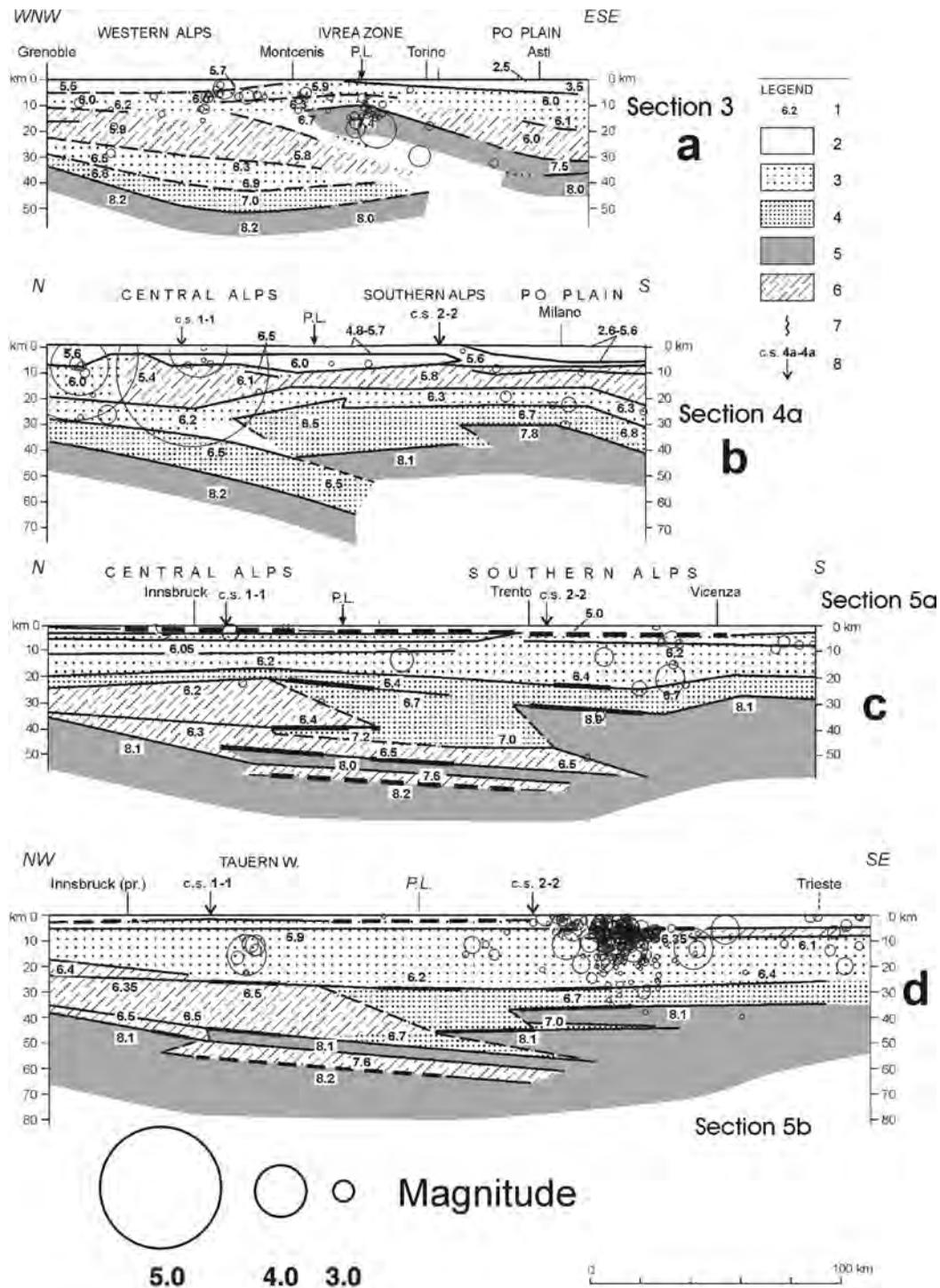


Fig. 4 - Interpretative transects across the Alpine range.

Explanation of symbols, common to all cross-sections (Figs. 4, 5, 7, and 10):

1 - velocities in km/s; 2 - surface layers ($V < 6.0$ km/s); 3 - upper or undifferentiated crust ($V = 6.0 - 6.5$ km/s); 4 - lower crust ($6.5 - 7.5$ km/s); 5 - upper mantle ($V > 7.5$ km/s); 6 - low velocity layers; 7 - coastline; 8 - crossings among sections. P.L.: Periadriatic Lineament. c.s.: cross-section. The interpretation of all the c.s. is the one proposed by Cassinis *et al.* (2003). The hypocentres are plotted after the catalogue by Chiarabba *et al.* (2005). The radius of circles

is proportional to M_d or to M_l (see text for details on the accuracy of focal depth as well on the criteria followed for the selection of the events).

a): 3 section, across the western Alps, from Grenoble to Torino and the Po valley. The seismic activity outlines the crustal doubling beneath the "Ivrea body" and the folds of the shallow structure in the western Alpine range.

b): 4a section: a portion of the European Geotraverse, crossing the western-central Alps. The seismicity seems confined to the upper crust near the crossing with the c.s. 1 section.

c): 5a section: crossing the central-eastern Alps from south Bavaria to the Euganei Hills (near Vicenza). Seismicity is observed near Innsbruck (crossing of c.s. 1 section) and in the region of the Giudicarie tectonic line. A deep hypocentre is observed corresponding to the northern end of the interpreted edge of the Adriatic Moho overthrusting the European plate.

d): 5b section: south Bavaria - eastern Alps - Friuli - Trieste. The earthquakes seem to concentrate in the upper crust, in the transitional area between the European and the Adriatic crust (Friuli seismic zone). Some events are also seen beneath the Tauern window.

Authors quoted in the above-mentioned paper was followed; when alternative versions were available, a critical choice was made, considering also the results of other adjacent or intersecting profiles.

It has to be called that the only physical parameter that can be determined (with variable accuracy) is the velocity of the P waves. Therefore, petrological and rheological models can be derived only through the assumption of hypotheses on rock composition and with the help of complementary data, like the heat flow.

A short description for each transect follows; the captions to Fig. 4 illustrate the meaning of symbols and the scale of M ; they are common to all the cross-sections shown.

3.1. Alpine region: sections across the mountain range (Fig. 3)

- Section 3, (Fig 4a) across the Western Alps, from Grenoble to Torino and the Po Valley. The overthrusting of the Adriatic crust on the European plate is clearly shown, the Adriatic upper mantle being lifted to about a 10 km depth in the Ivrea zone; The shape and extension of this complex of high-density, high-velocity and high-susceptibility rocks, exhibiting a positive gravity effect of some 180 mGals, is still under debate. In particular, it is not clear whether it has a continuation into the deeper crust or if it is limited to the bottom of the Padan crust. The reconstruction in Fig. 4a clearly shows that the area is characterized by a frequent, clustered seismic activity. Some seismic events border the thrusting of the Adriatic crust down to a 40 km of depth. Whereas proceeding westwards, the seismicity seems confined to the upper crust (Alpine nappes), within a 10 km depth.

- Section 4a, (Fig. 4b) (stretch of the "European Geotraverse"), crossing the western-central Alps, from the Molasse basin to the Penninic units, the Bergamasc Alps and to the Po Valley south of Milan. In the central-southern Alps the overthrust of the Adriatic on the European plate is shown, the edge of the Adriatic upper mantle being positioned near the Peri-Adriatic Lineament. The front of the Adriatic lower crust appears shifted about 15 km north. The European upper mantle deepens southwards reaching a depth of about 60 km, then is lost, along the whole Alpine range. The Adriatic Moho is 30-40 km deep, beneath the Po Valley. The seismic activity in the northern part of the cross-section (corresponding to the beginning of the interpreted subduction of the European plate at about a 40 km depth) is relatively shallow and of high magnitude. In a very small area, four events with magnitude greater than 4.0 (4.1, 4.1, 4.8 and

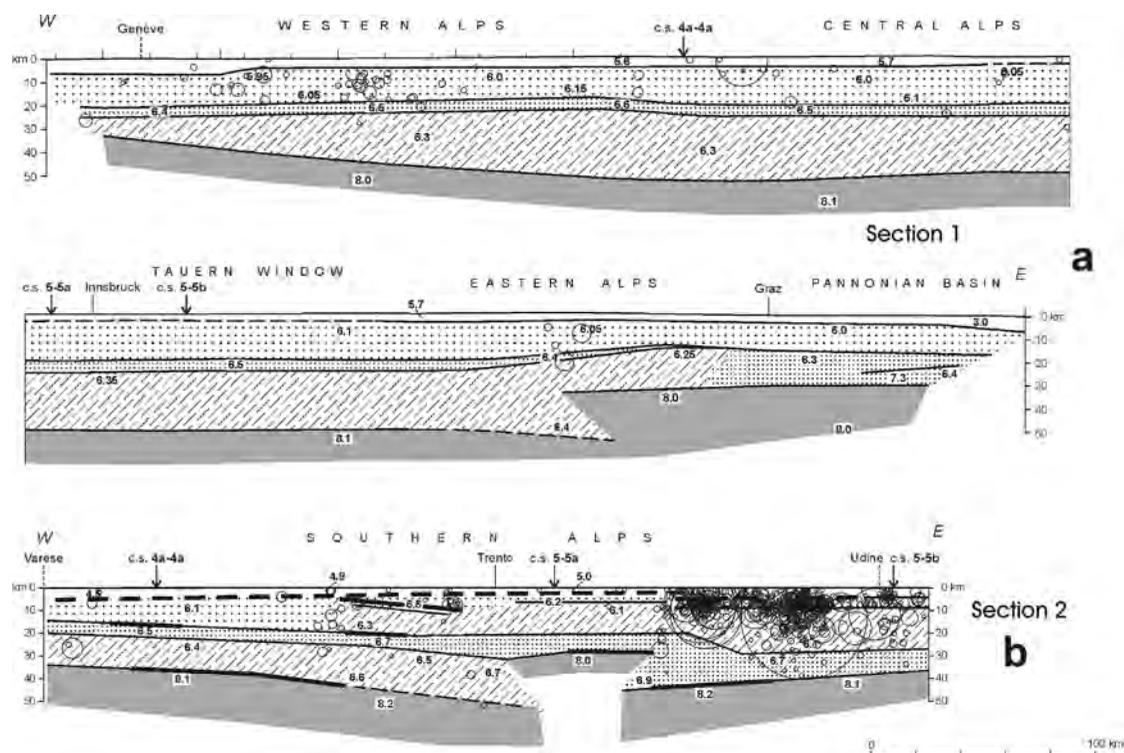


Fig. 5 - Alpine region: profiles along the strike (the crossing points with the sections of Fig. 4 are indicated).

a): section 1 (Western Alps - central Alps - eastern Alps - Pannonian basin). The seismicity, confined to the upper crust everywhere, shows its maximum in the central-western Alps, east of Geneva; some events are recorded above the Moho step marking the transition to the Pannonian domain.

b): section 2 (Lombardian southern Alps - southeastern Alps - Udine) Some small deep earthquakes are observed beneath the Giudicarie line west of Trento. The major seismic zone (Friuli) can be correlated with a sudden change of thickness of the intermediate crust at the western end of the area, as well as with the lifted block of the upper mantle.

5.2) occurred in the period covered by the catalogue; in particular, the last one was the main-shock of a rather long seismic sequence [Penninic Alps, see Deichmann (1992)] the aftershocks of which did not exceed magnitude 2.5 and did not occur deeper than 10 km. An almost quiescent area is that of the central Alps starting from the crossing with section 1; some events of low magnitude are recorded when the Po Valley is reached; they seem to be well consistent with the layering of both the upper and lower crust.

- Section 5a, (Fig. 4c) crossing the central-eastern Alps from southern Bavaria near Munich to the Euganei Hills, south of Vicenza. In this transect, the European crustal domain appears to be extended southwards well beyond the Peri-Adriatic Lineament; it seems to become flatter in the southern sector, where a depth of 55 km is reached. The overthrusting of the Adriatic upper mantle (30 km deep) on the European mantle is positioned beneath the city of Trento. The Adriatic lower crust layers override the European lower crust here too but their front appears to be shifted northwards to a much larger extent than along the former transect. Some seismicity is observed near Innsbruck (crossing of section 1) and on the Giudicarie line south of Trento. A couple of deep events border the overthrusting of the Adriatic upper mantle.

- Section 5b, (Fig. 4d), southern Bavaria-eastern Alps- Trieste, again shows a modification of the deep structure, especially at its south-eastern half. The edge of the Adria Moho is less sharp than in the former transects and appears to be bent north-eastwards; the wedge extension is smaller than in transects 4a and 5a. Therefore, it seems that the last pushes also influenced the Adria upper mantle in the easternmost Alpine section. The thickness of the Adria crust is about 35 km and is reduced as it approaches the Adriatic shore. It can also be remarked that the reinterpretation of the deep crustal structures in the central-eastern Alps (Scarascia and Cassinis, 1997) was confirmed by the results of the seismic reflection profile "TRANSALP" (Transalp Working Group, 2002). The seismicity is mainly concentrated in the upper crust. Some hypocentres are shown at the bottom of the low velocity material filling the Tauern window. The rest of the seismic activity is clustered close to the area of occurrence of the 1976 Friuli earthquake with magnitudes up to 4.0; it is confined within the crust. Only few and small deep events border the crust-mantle transition. The strongest activity falls in correspondence to the area of the transition between the European and the Adriatic crust.

3.2. Alpine region: sections along the strike

- Section 1, (Fig. 5a) north-western Alps-central Alps-Pannonian basin (ALP '75). The crustal structure appears homogeneous along the central part of the profile, having a fairly constant total thickness of about 50 km, while the one of the lower crust is about 20 km thick, its seismic velocity being abnormally low. A gentle uprising of the Moho boundary is observed at the western end of the profile up to the depth of 30 km, beneath the city of Geneva. In the transition zone from the eastern Alps to the Styrian and Pannonian basin the Moho suddenly rises from 55 km up to 30 km. Events are shown, in the upper rigid crust, at both ends of the line, in the Pennides east of Geneva and above the Moho sharp step marking the transition to the Pannonian basin. Seismicity is absent in the central part of the profile (north central Alps) except near the crossing with section 4a (see above).
- Section 2, (Fig. 5b) Varese-Udine. This line follows approximately the "Sud Alp" refraction profile, on the Lombardian-Venitian southern Alps. In the Lombardian domain, the Moho boundary deepens eastwards from 33 to 45 km. Beneath the Euganei hills a sudden uplift up to 28 km of the upper mantle is shown in agreement with the strongly positive Bouguer anomaly (see Fig. 1). The thickness of the lower crust is about 20-30 km in the western sector, while it is reduced to about 10 km beneath the Euganei Hills and in the eastern sector. The hypocentres are assembled in the upper crust in two main areas: the first one is situated across the Giudicarie line, west of the city of Trento, where a near shot allowed the interpreting teams to make a detail of the shallow structure; here, the seismicity seems to happen at about 10 km, where a velocity inversion was interpreted. Some events of small magnitude are as deep as 20 km. The second area is Friuli (west of the intersection with section 5b); here the earthquakes are mainly concentrated along the boundary between the shallow upper ($V_p=6.35$ km/s) and the intermediate crust (V_p about 6 km/s); however, several events are positioned in the intermediate crust as well. It can be remarked that this area is situated above the eastern end of the lifted upper mantle fragment. All through the cross-sections, few events border the deeper structures; in particular, the seismic activity close to the mantle at a 28 km depth is worth noting. It can also be recalled that the velocity functions in the Friuli area (Cassinis and Ranzoni, 1987) were

compared with the theoretical V_p functions calculated for different values of the heat flow, according to the crustal model. Maximum stress curves were computed accordingly and compared with the depth distribution of an aftershock sequence: the maximum magnitude and energy fall at the boundary between the brittle upper crust and the more ductile intermediate crust. It must again be remarked that the rheological properties were only hypothesised, the sole known parameter being the compressional velocity.

3.3. Apenninic transects (Fig. 6)

- Section 4b (Fig. 7a) is another stretch of the European Geotraverse from the Po Valley north of Genova to the Ligurian Sea and Corsica. The Padan-Adriatic crust is seen sinking beneath the coastal chain and the transitional Ligurian-Tyrrhenian crust; this section shows the rise of the oceanic Moho (with velocity of the order of 7.5 to 7.8 km/s) similarly to what was revealed by seismic tomography (Eva *et al.*, 2001). The seismicity clearly follows the change of crustal type; more southwards another, weaker, seismic zone marks the transition to the continental type of crust of Corsica.

- Section 7 (Fig. 7b), from the western Mediterranean, crosses Corsica, the Island of Elba, southern Tuscany (geothermal area), reaches the city of Perugia, the Tiber Valley and finally the Adriatic coast near the city of Ancona. Several typologies are revealed in this section: a thinned crust is interpreted in the western Mediterranean basin (thickness of about 20 km), a continental

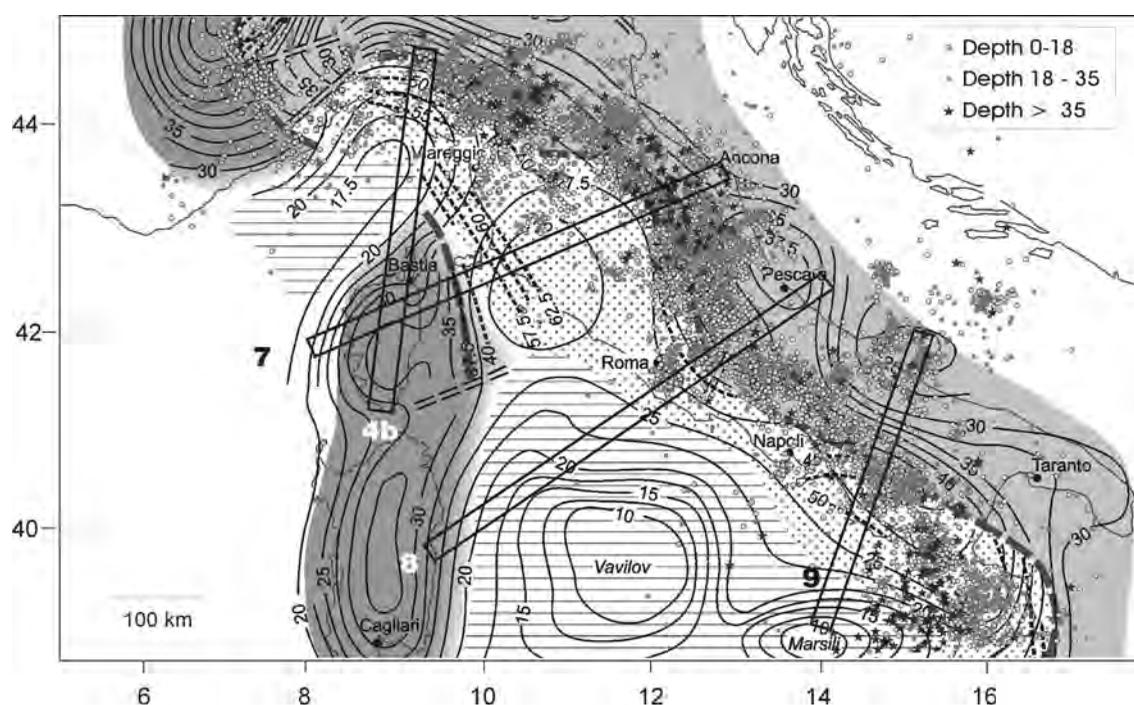


Fig. 6 - Enlargement of Fig. 2 (North, Central and Southern Apennines). The traces of the cross-sections described in Fig. 7 are shown.

crust beneath Corsica (about 30 km thick) where the upper mantle layers deepen in the NE direction, to disappear under the Elba channel. A shallower Moho appears to override the continental crust; east of this boundary, a thinned type of crust is observed (Perityrrhenian-Tuscan), characterised by low-velocity layers in the lower crust, which stretches from the Island

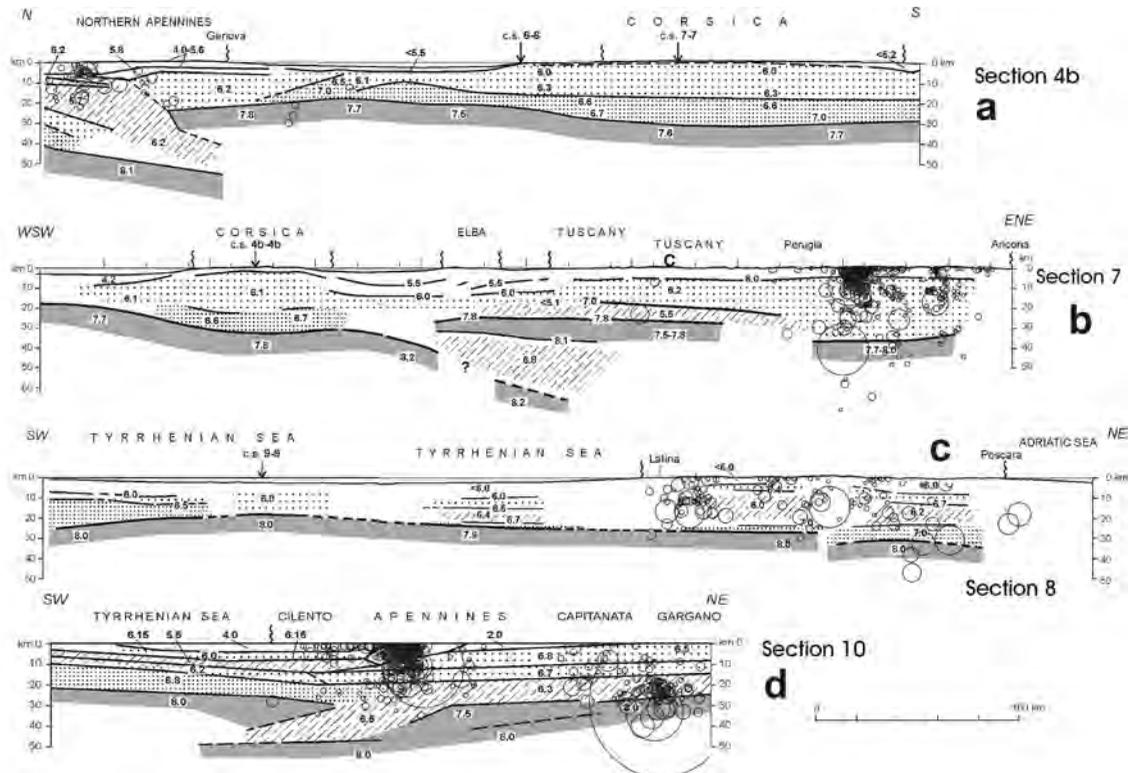


Fig. 7 - Apenninic transects:

a): section 4b: Northern Apennines - Ligurian Sea - Corsica (section of the European Geotraverse). The seismicity clearly corresponds to the northern Apennines and to the beginning of the subduction of the Padan - Adriatic crust beneath the Ligurian transitional crust. Further south, a weaker activity marks the transition to the continental type of crust beneath Corsica.

b): section 7: Western Mediterranean - Corsica - Elba - south Tuscany - Perugia - Tiber Valley - Ancona on the Adriatic shore. The western part of the profile follows the path of the reflection line CROP 03.

The absence of seismic activity beneath the Island of Elba, has to be interpreted as evidence that the subduction of the European crust is no longer active; however, it has to be noted that the distribution of seismic stations in that area is poor. The very shallow seismicity in the geothermal region of Tuscany was not recorded by the national seismological network during the considered period.

The active subduction of the Adriatic plate is clearly put in evidence. See text for more comments and Fig. 8 for a comparison with a deep seismic reflection line.

c): section 8: south Sardinia - Tyrrhenian Sea - central Apennines - Adriatic coast near Pescara. The seismicity occurs at both sides of the step (less clear than in section 7) that appears to mark the transition to the Adriatic plate. The hypocentres show the Adria subduction as in section 7. A remarkable activity is observed in the volcanic area south of Rome, on the Tyrrhenian shore of Latium.

d): section 10: south Tyrrhenian Sea - Cilento - southern Apennines - Gargano promontory. The earthquakes are concentrated in two areas: beneath the Apennines, (where the Adriatic plate is over-thrusted by the thin Peri-Tyrrhenian crust) and near the Adriatic coast (Gargano). In the former area the distinction between the shallow events connected with the Apenninic folds and the deeper ones that follow the Adriatic subduction is clear. Beneath the Gargano promontory the hypocentres seem to concentrate closer to the Moho boundary.

of Elba up to Perugia and the Tiber Valley. Near Perugia the crust suddenly thickens and the low-velocity layers disappear, showing that the Adriatic plate is reached. The seismic regime along the profile is very variable: the absence of recorded seismicity beneath the Island of Elba and the coast of Tuscany might depend on the uneven distribution of seismic recording stations on the noisy coast of Tuscany and in the sea, but seems to confirm that the high velocity fragment 50 km deep, dipping eastwards, does not represent any active subduction process but is probably only a heterogeneity inside the upper mantle. Within the geothermal region of Tuscany the activity is confined to the shallow crust at depths of between 3 and 10 km, as shown by the many events recorded by local seismic networks. In the period considered here (1981-2002) the swarms of small events that characterise this region are not shown in the catalogue. Proceeding eastwards, a very clear correlation of the hypocentres with the Adria subduction westwards is shown: the seismicity is distributed throughout the whole of the crust whose behaviour, therefore, appears to be rigid up to the upper mantle; the hypocenters deepen westwards down to a depth of 60 km or more. The Adriatic Moho is interpreted in the DSS profile as a flat boundary at a depth of 35-40 km, but considering the distribution of seismicity with depth, a westward dip seems more acceptable.

In Fig. 8 an interpretation (line drawing) of the CROP 03 deep reflection profile (Gualteri *et al.*, 1998) is recalled. This line does not coincide with the DSS 7 transect, as the Adriatic coastline is reached at Pesaro, about 20 km north of Ancona. Anyway the two lines can be compared. At its eastern end the “line drawing” shows short reflecting elements (actually mainly diffractions) steeply dipping westwards. The earthquakes (taken from a compilation of data different from the one used in the present paper) deepen also westwards, showing a similar trend. Therefore, it is felt that in this case the epicentres confirm the hypothesis of an active subduction westwards better than the DSS.

- Section 8 (Fig 7c), Southern Sardinia-Tyrrhenian Sea-central Apennines-Adriatic coast near Pescara. The continental European crust of Sardinia is about 30 km thick, 12 km being the

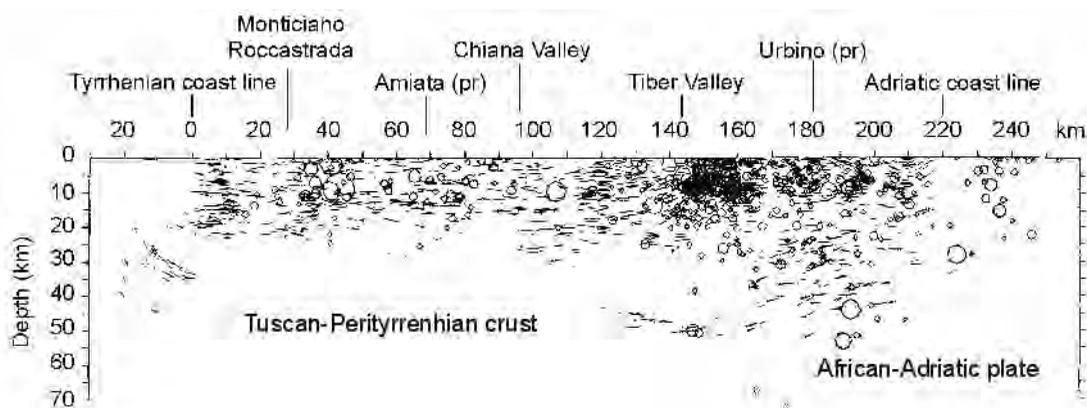


Fig. 8 - A line drawing (depth migrated) (Gualteri *et al.*, 1998) of the NVR profile CROP 03, partly overlapping the DSS profile of Fig. 7b (section 7), and reaching the Adriatic coast about 20 km north of the latter. The hypocentres are taken from a different compilation of data; however, the focal depth of the earthquakes as well as the average dip of reflections confirm the active subduction of the Adriatic plate.

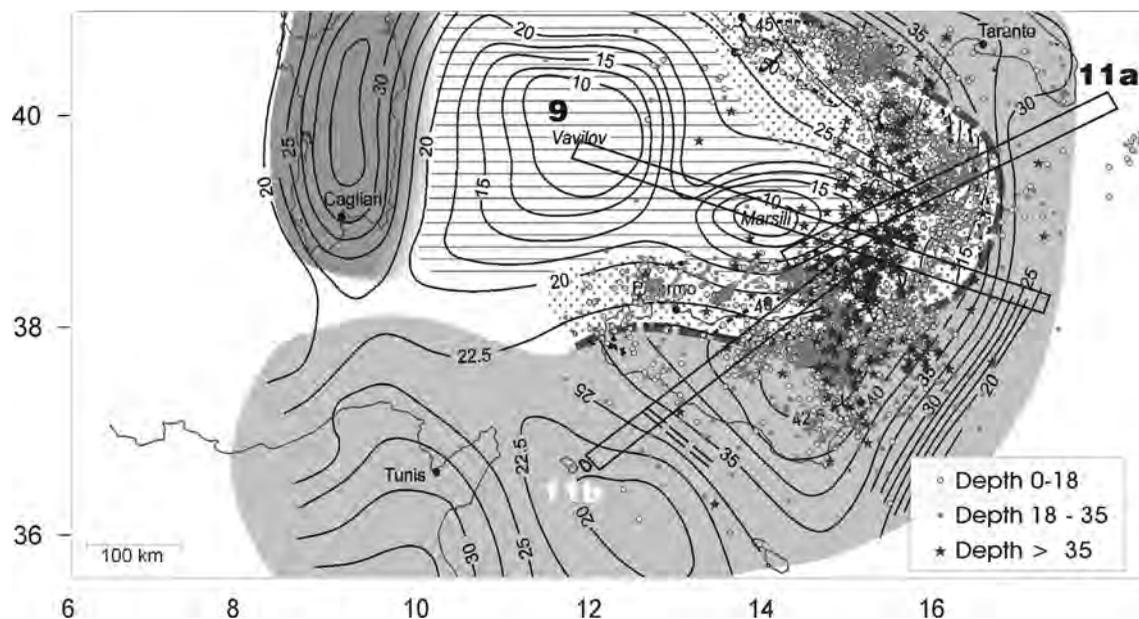


Fig. 9 - Enlargement of Fig. 2 for southern Italy and Sicily. The traces of the cross-sections described in Fig. 10 are shown.

thickness of the lower crust. The crustal structure and the typology change in the Tyrrhenian Sea where the minimum thickness is of 18 km. In the stretch between Latina and Pescara a transition between the Perityrrhenian thinned crust and the Adriatic plate is seen, similar to that observed in section 7 but less clear. The seismicity is concentrated beneath the Apennines on both sides of the step. A group of deeper events of medium M is recorded, steeply dipping westwards, showing a behaviour similar to the one observed on section 7. A remarkable activity is observed too in the volcanic area south of Rome.

- Section 10 (Fig. 7d), South Tyrrhenian sea-Cilento-Gargano promontory-Adriatic coast. In the transitional zone a thinned crust (22-25 km thick) extends from the Tyrrhenian Sea to the coast of Cilento. Here a subduction process of the Adriatic plate beneath the Perityrrhenian crust is shown, the Adriatic Moho boundary reaching a depth of 50 km. The Adriatic crust thins eastwards, approaching the Gargano promontory where the Moho is found at 24 km. The strongest seismic activity occurs beneath the Apenninic range; it is directly connected with the complex structure of the upper crust; however, it should be pointed out that, like in section 7, the events are concentrated in the area where the subduction is originated. It can be remarked too that some low/medium magnitude hypocentres are positioned along a line where a lateral change of velocity was interpreted in the lower crust, also in the subduction area. The Gargano promontory exhibits a particular seismic regime: here the main activity appears positioned on the crust-mantle boundary. The most important earthquake for the period under study is the M1 5.4 of September 1995, but several events occurred in the vicinity; they appear very clustered. It must be remarked that the crustal structure beneath the Gargano proper cannot be detailed by the DSS data as the promontory is situated at the far eastern end of the seismic line.

3.4. South Tyrrhenian, Calabrian-Aeolian arc, Sicily, Salentina peninsula (Fig. 9)

- Section 9 (south-eastern part; Fig. 10a), central Tyrrhenian Sea mounts-Calabrian arc-Ionian Sea). The typology of the crustal structure along the Tyrrhenian basin can be defined as oceanic or, in some areas, sub-oceanic. Due to the low density of receivers (bottom seismometers) the velocity of the crust is assumed to be constant (6.0 km/s) but the one of the upper mantle is accurately determined by the Pn arrivals, and ranges between 7.7 and 8.0 km/s. Two minima of crustal thickness were found near the Vavilov and Marsili volcanoes (10 km). The structure becomes more complicated beneath Calabria and the Ionian Sea where a thinned crust (about 15-20 km thick) over-thrusts a thicker crustal type, the latter representing the northernmost extension of the African plate. Some hypocenters of medium M are recorded at the crust-mantle boundary beneath the Marsili sea mount and offshore the Tyrrhenian coast of Calabria. A strong seismicity in the thin crust is found crossing the mainland where the crustal structure appears

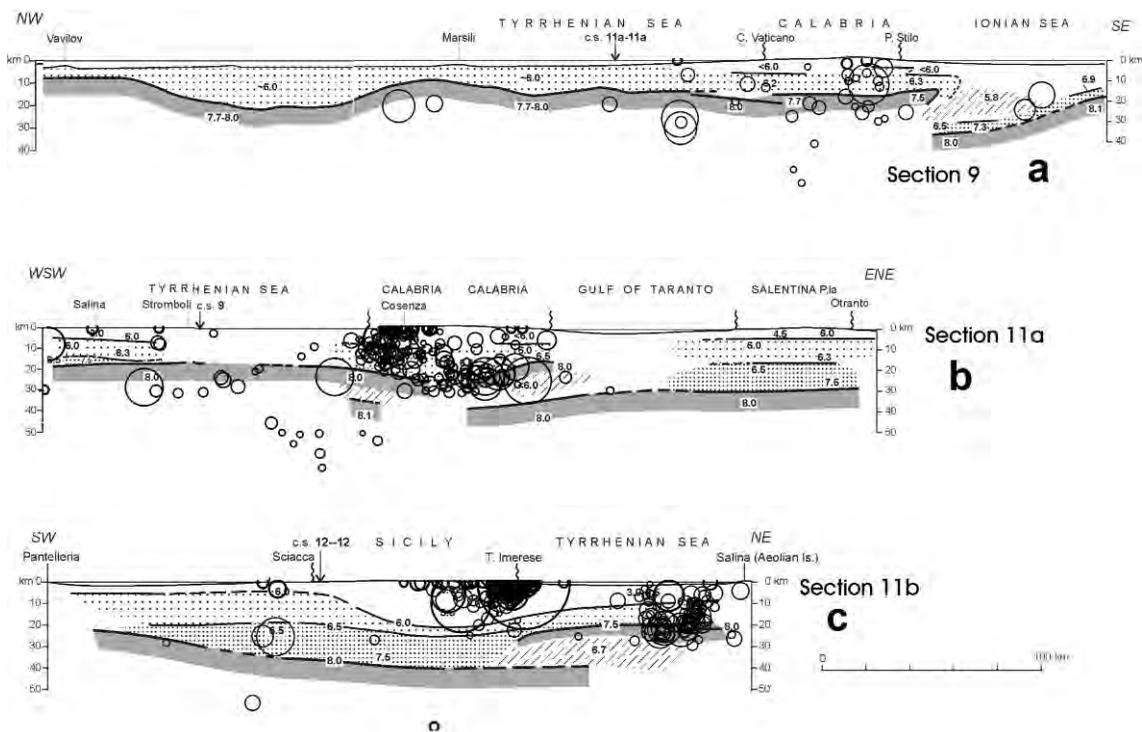


Fig. 10 - Interpretative cross-sections in south Tyrrhenian, Calabrian-Aeolian arc, Sicily, Salentina peninsula.
 a) Section 9, central Tyrrhenian Sea mounts - Calabria - Ionian Sea. The strongest seismicity is found while approaching the mainland of Calabria. The subduction of the Aeolian arc clearly originates south-east of Calabria, in the Ionian Sea where the over-thrusting of the Tyrrhenian crust on the African plate is observed.
 b) Section 11a, Aeolian Islands - Calabria - Gulf of Taranto - Salentina peninsula. The strongest seismicity is found in the thin crust beneath Calabria, where the beginning of the Aeolian arc is seen. Further to the north-east, the gulf of Taranto and the Salentina peninsula (margin of the Adriatic plate) appear almost aseismic.
 c) Section 11b, Sicilian Channel (Pantelleria Island) - western Sicily - Tyrrhenian Sea - Aeolian Islands. The earthquakes are concentrated in the north-western margin of the thick sediments of the Caltanissetta basin as well as near the Aeolian Islands.

more complex than in the central Tyrrhenian; when the Ionian Sea is reached the beginning of the lithospheric subduction of the Aeolian arc is very clearly observed.

- Section 11a (Fig. 10b), Aeolian Islands-Calabria-Gulf of Taranto-Salentina peninsula. A thinned crust is shown (about 20 km) below the Tyrrhenian Sea and Calabria. The Adriatic crust in the Salentina peninsula is 30 km thick and the Moho boundary deepens towards Calabria where an extended subduction zone is interpreted. This profile crosses the section 9 on the Aeolian Islands; the strong seismicity of Calabria is distributed through whole of the crust, the highest *M* occurring at the crust-mantle boundary; also here the start of the Aeolian arc is clearly shown by the hypocentres deepening into the upper mantle. The geometry of the layer at a 40 km depth under Cosenza (8.1 km/s) could be slightly different from that proposed by the DSS studies: the distribution of seismicity seems to suggest that it could be a little deeper and more extended westwards. The Gulf of Taranto and the Salentina peninsula (Adria-African plate) seem nearly aseismic.
- Section 11b (Fig. 10c), Pantelleria-Sciaccia-Aeolian Islands. In the south western section of the transect, the crust, ascribed to the African plate, is 22 km thick in the channel of Sicily and thickens when approaching the southern Sicilian coast where it reaches 40 km. The profile crosses the westernmost part of the Caltanissetta trough which is filled by about 20 km of sediments, as witnessed by a very strong negative isostatic gravity anomaly, the coastal chain being made of isolated allochthonous blocks of carbonatic rocks. The hypocentres are concentrated both here (where they are shallow) and in the northwestern part of the profile (Aeolian Islands) where the crustal doubling is again observed of the Tyrrhenian crust overriding the margin of the African plate; here the stronger events occur at the Moho boundary.

4. Concluding remarks

The comparison between the seismic activity and the interpretative cross-sections based on the results of DSS data in the Italian region, although subjected to limitations due to the short time period considered by the seismic catalogues, may be used to derive some general considerations:

- The interpretation of DSS profiles, though based exclusively upon the velocity of compressional seismic waves, appears to be validated by the remark that seismicity is mainly concentrated where structural changes are observed in the cross-sections.

It should be noted that this goal has been reached despite the fact that the acquisition techniques of the DSS described here are, nowadays, obsolete. Unfortunately, shots are no longer allowed in Italy, either inland or offshore, therefore new acquisitions using updated techniques are impracticable. Nevertheless, the archive of digitised DSS data can again be used to further refine the interpretation, especially by integration with other investigative methods, namely, passive seismic tomography for the study of the upper mantle and near vertical reflection seismic profiles to obtain details of the structure of the upper crust.

- The seismic activity in the Italian region originates mainly in the upper rigid crust: here the seismicity is often of low to medium magnitude while, especially in southern Italy, the strongest events occur at greater depths within the crust or at the Moho boundary. It must be remarked that even the events happening within the upper crust seem very often to be in correlation with the structural elements interpreted in the lower crust or at the Moho boundary. It is still an open

question of how the stress can be transferred from ductile or semi-ductile regions to shallower, rigid rocks.

- Deeper hypocentres (at the Moho boundary or in the upper mantle) are especially observed where a process of active subduction is taking place. There, the distribution of hypocenters define the direction and dip of the subduction process and complement the findings of the DSS. It must be stressed that the penetration of the latter technique of investigation was limited, in every case, to a depth of about 50-60 km.

This study shows that the seismic regime changes according to the crustal structure and the Moho boundary characteristics, thus yielding further elements to the study of the complicated geodynamic behaviour of our region.

The results described here also suggest that they could be used as additional elements for the study of seismogenesis; in particular, they show that events of similar magnitudes originated by the same structure may occur at different depths. This can influence the effects of the earthquake on the surface and, indirectly, the studies on hazard, which do not take into account the focal depth.

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