SEISMICITY OF THE UPPER LITHOSPHERE AND ITS RELATIONSHIPS WITH THE CRUST IN THE ITALIAN REGION

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ABSTRACT

In a recent paper we compared the earthquake hypocenters, plotted according to updated catalogs, with the structure of the earth's Crust interpreted after the results of seismic exploration (mainly the Deep Seismic Soundings – DSS). The comparison was made along several cross sections in the Alpine range, the Italian Peninsula and the surrounding seas. The main conclusions of this analysis were that 1) the majority of the events is positioned in the upper, rigid crust and 2) the earthquakes tend to concentrate above the discontinuities unveiled by the seismic exploration in the deep crust and at the Moho boundary.

With the goal to shed some light on the continuation of these structures with depth, in this paper a similar analysis is conducted even in volumes where DSS information are not available. It is apparent that the upper mantle seismicity is very unevenly distributed; therefore we only focus on the areas where a sub-crustal seismicity is recorded, adding to the seismic models of the crust some information, if available, on the physical characters of the upper Lithosphere.

Four areas are examined: the well known Calabrian (Aeolian) Arc where the Ionian plate is subducted beneath the Tyrrhenian, thin crust of oceanic type, the active subduction of the slab being witnessed by deep and very deep earthquakes; the north-central Apennines where the continental crust of the Adria microplate seems also subducted beneath the transitional, peri-Tyrrhenian type of crust but where the observed hypocenters are limited to the depth of about 100 km; the northern Apennines, where the same type of subduction seems to occur beneath the north-eastern slope of the mountain

range, though evidenced by an even smaller number of events; finally, the western Alps: also here a small group of foci are recorded in the upper Mantle beneath the southern end of the “Ivrea body”.
The different behavior of deep seismicity in the four areas confirms that the Italian peninsula is formed of sectors deriving from different geodynamical processes.

FOREWORD

In a preceding paper (Cassinis et Solarino, 2006) the results of an analysis to investigate the relationships between seismicity and the main features of the crust beneath the Italian peninsula were presented. In that study, two data sets were compared: the interpretation of the Deep Seismic Soundings – DSS along several transects, crisscrossing the Alpine range and the Italian Peninsula (Cassinis et al., 2003, 2005), and an updated catalog of the earthquakes (Chiarabba et al., 2005). The most important conclusion was that, while the majority of the earthquakes happens in the rigid, upper crust, the hypocenters are assembled above the discontinuities discovered by the DSS in the lower crust and at the Moho boundary. Since the maximum depth of the DSS is limited to the crust-mantle boundary, few information were obtained on the continuation with depth of the tectonic structures below that limit. Therefore, only in few cases the upper bend of subduction zones was imaged and investigated.
Royden et al, 1987, had already pointed out that subduction-zone processes and their control on surface deformation are poorly understood, largely because few direct methods are available for observation of such process. Nevertheless, some steps towards a more detailed knowledge of the subducting plates have been achieved in the last years using indirect techniques, like, for example, seismic tomography (see for example Solarino et al. 1996 or Di Stefano et al., 1999). The increasing available images of the subduction areas have favored several hypotheses on their nature and evolution; a discussion of these models is beyond the scope of this paper and will not be treated here.
In this study we integrate the information on the crust, already described by the seismic exploration, with a very well constrained distribution of seismicity, in order to infer the continuation at depth of the most debated structures.

In fig. 1a the hypocenters recorded in the Italian region during the period 1981-2002 (Chiarabba et al, 2005) are projected on a NW-SE cross section; it is clear that they are concentrated within the depth of 25 – 30 km; however, five areas are observed where a sub – crustal seismicity is recorded, namely, proceeding from NW to SE, south western Alps, north Apennines, north central Apennines, southeastern Alps (northern Dinarides) and, finally, Calabria-south Tyrrhenian Sea (the well known Aeolian slab). From this synthetic approach It can be remarked that the maximum depth reached by the earthquakes as well as the number of events in the areas above are increasing while proceeding from NW to SE.

In fig.1b the distribution of magnitude versus depth is plotted for the share of the data base where this parameter is known (about 50% of the events); it is shown that the threshold of the high M events (> 5) is found within the depth of about 30 km.

SEISMIC ACTIVITY AND CRUSTAL DOMAINS

In fig. 2 the crustal domains, the Moho depth contour lines and the tectonic features in the deep crust and at the crust-mantle boundary are described according to a revision of the interpretation of DSS lines (Cassinis et al., 2003, 2005, Cassinis et Solarino, 2006). The traces of the interpretative transects that will be discussed later are plotted: the empty ones indicate the cross sections along which the interpretation of the crustal structure is available, while the grey filled traces correspond to those where only the seismic events are plotted. In both cases, the hypocenters contained in a variable width (20 to 30 km) are projected on the vertical section.

In fig. 3 the epicenters are plotted on the map of fig. 2. Two classes of depth are considered:

Z < 35 km (mainly inside the crust), (fig. 3a), and Z > 35 km (mainly in the upper lithosphere), (fig. 3b). The choice of such a value has been done on the basis of the average position of the Moho for the Peninsula (fig. 2) and of the findings of Chiarabba et al., 2005, which underlined a very clear difference in the seismicity above and below that depth.

The magnitude is also shown. The accuracy of both vertical and horizontal coordinates is within +/_ 3 km for all events: it allows to discard those events having an arbitrarily depth assigned during the location process; furthermore, in this way the uncertainty in the hypocentral position is comparable with the size and depth of the cross sections traced on the map. For comments on the correlation of the epicenters position with the interpreted features in the crust and in the Moho boundary, reference is made to Cassinis et Solarino, 2006. Comparing the two maps (figs. 3a and 3b), it is very clear the shifting north westwards of the deep epicenters of the sinking Aeolian slab.

DESCRIPTION OF SEISMIC ACTIVITY ON THE SELECTED CROSS SECTIONS

In the five investigated areas a sub crustal seismicity is recorded and reliable models of the crust are available. For the sake of clarity, we assigned to the DSS cross sections the same numbers that were used in the previous papers (Cassinis et al., 2003, 2005, Cassinis et Solarino, 2006).

Let's start examining the area of the Calabrian (Aeolian) Arc; in fig. 4 the interpretation of the DSS transect 9 – 9 (Steinmetz et al., 1983) from the center of the Tyrrhenian Sea to Calabria and to the Ionian Sea is proposed, and all the available hypocenters are projected on the vertical section; they clearly show the shape of the subducting slab, down to the depth of about 300 km. The onset of the slab is in the Moho step that marks the transition from the margin of the Ionian domain to the Tyrrhenian, thinner crust. Note that the crust of the Ionian plate (Makris et al., 1986; Scarascia et al., 1994) is thicker (about 20 km instead of 10 – 15 km of the Tyrrhenian) and is characterized by a thick sedimentary low velocity cover.

In fig. 5 cross section 11a is described from the Aeolian islands to Calabria, the gulf of Taranto and reaching the tip of the Salentina Peninsula. Note the contrast between the SW part of the section (strong seismic activity beneath the Aeolian islands and Calabria where the beginning of the slab is observed) and the NE portion (continental type of crust belonging to the African plate) where the earthquakes are almost absent.

The seismic foci are also plotted on three cross sections directed nearly normally to the 11a; the north eastern section shows the termination of the slab in that direction. While in the 11a the seismic activity is continuous, though of variable M, along the whole slab, in the two cross sections traced south westwards two gaps, respectively at the depth of about 130 and 60 km, can be observed.

The second investigated area is in north central Apennines; in fig. 6a the interpretation is illustrated of cross section 7 –7 from Corsica to the Elba channel, south Tuscany, the Apenninic range, the city of

Perugia, the Tiber valley and the Adriatic coast near the city of Ancona. The highest magnitude seismicity is concentrated in the upper crust, above the step of the Moho boundary near Perugia (eastern side of the Apennines). The foci (max depth 80-90 km) deepening westwards beneath the Adriatic coast seem to indicate the beginning of the subduction of the Adria microplate. Here the trend of the hypocenters agrees with the interpretation of the deep reflection line CROP 03 that reaches the coast at Pesaro, about 60 km north of Ancona; the deeper recorded events (mainly diffractions) outline the westwards immersion of the thicker Adria crust, in contrast with the flat pattern peculiar of the Tuscan-Tyrrhenian thin crust, characterized by high heat flow, (see the interpretative models by Barchi et al., 1998, Decandia et al., 1998, Gualteri et al., 1998, Cassinis, 2002 and also Cassinis et Solarino, 2006) . In fig 6b a line parallel to section 7-7 (about 80 km to the south) shows that the deep earthquakes have almost disappeared.

In fig 7 the DSS line 6-6 is illustrated (see also Scarascia et al., 1994; Letz et al., 1977), from the Ligurian sea north of Corsica to the coast of northern Tuscany near Viareggio, then crossing the northern Apennines. A moderate seismic activity is observed beneath the mountain range and also here a small group of deep foci (70 - 80 km) is shown. The foci are plotted on sections perpendicular to line 6-6: no seismicity in the upper mantle is recorded beneath the coast of northern Tuscany and the Ligurian sea.

Tomographic images obtained by using different methods show in the northern Apennines a pronounced high-velocity anomaly, interpreted as a submerged crustal slab, representing the westward continuation of the Adriatic Moho. The shape and location of the imaged high velocity slab are slightly different, reflecting difference in model resolution obtained by using local, regional and teleseismic data. In particular, the slab continuity is still debated. Lucente et al., 1999 and Piromallo et Morelli., 2003, define a continuous slab down to 670 km depth, while Spakman et Wortel, 2004, hypotesize a relatively short (300-400 km) and continuous northern Apennines slab which may strongly curve to the west beneath the Po plain. In their view, a short north-Apennines slab is sufficient to explain the opening history of the northern Liguro-Provençal basin. Moreover, the negative anomalies imaged in their tomographic images to depths of 200 km under the central-southern Apennines are attributed to slab detachment. Such geometry would justify the absence of earthquakes beneath 100 km under the whole Central Apennines.

In fig. 8 the cross sections across the Western Alps are illustrated. The interpretation of the central section (3), Grenoble-Turin-Po Valley) (one of the earlier recorded, see also Giese et Prodehl, 1976) is controversial; the one here presented (Cassinis et al., 2003; Cassinis et al., 2003, 2005) was assumed as the most likely: the shallow fragment having a velocity of about 7.5 km/s is attributed to the lifted and impoverished mantle material belonging to the Adriatic-African domain, overthrusting the European Moho that is subducted south westwards, beneath the Po Valley. The deep reflection line (Nicolas et al., 1990) did not confirm this hypothesis, that is, in turn, supported by gravity anomalies. Along the section the seismicity appears to be confined to the upper crust, especially in the western side of the Alps; the foci very clearly follow the shape of the Moho fragment ("Ivrea body") on the eastern side. A similar pattern is observed along the parallel sections except in the southernmost one, where a small group of subcrustal events is recorded, positioned in the area where the European, Adria and Ligurian domains meet. The results of passive seismic tomography (Solarino et al., 1997; Eva et al., 2001; Scafidi et al., 2006) show that in the same area an anomalous high velocity is found in the upper mantle. This location corresponds also to the sudden change of direction of the gravity anomalies (see the insert in fig. 8, Klingele et al., 1992). Therefore, a different geodynamic behaviour of the sectors of the Alpine range is proposed and evidenced by the comparison of the two data sets used in this work.

CONCLUDING REMARKS

The main conclusion of a previous paper (Cassinis et Solarino, 2006) was that the seismic regime in the Italian region changes according to the crustal structure and to the Moho boundary characters.

In this paper particular attention is given to the sub crustal seismicity. It has to be remarked that the joint interpretation of DSS and seismicity alone cannot provide a complete frame of the structural, deep setting of the Italian peninsula. This happens for several reasons: the discreteness of information, the inhomogeneous distribution of seismic stations, with consistent gaps especially in the seas, the threshold of magnitude, and many others. Furthermore, it must be reminded that the max. penetration of DSS is of about 60-70 km. Nevertheless, the analysis highlights the complexity of the geological structure and the different geodynamic history of each sector of the Alpine range, of the Apennines as well as of the Calabrian Arc and Sicily. Earthquakes in the upper mantle are observed especially where a process of subduction is taking place. However, such process happens following different mechanisms.

The following synthesis of the results can be done:

- The lateral extension of the well known Aeolian-Calabrian-Ionian slab appears well defined, corresponding to the NE edge of the Ionian plate. The relationships between the crust and the upper mantle are clear: the onset of the subducting slab is in the step marking the transition from the Tyrrhenian (thin, oceanic type of crust) to the Ionian (thicker, oceanic type of crust). Unfortunately, in the Ionian plate the knowledge of some complementary data (heat flow, seismic activity) is not adequate for a more quantitative interpretation. Nevertheless the geometry, size and characteristics of the slab have been extensively studied by many tomographic experiments. Di Stefano et al., 1999 have underlined the presence of two broad low-velocity zones located beneath both the south-eastern portion of the Calabrian arc and the Aeolian islands, at slightly different depths. Our results show that, while the rigid behaviour of the main part of the subducting material is witnessed by the continuity of the earthquakes along the sinking slab down to about 300 km (cross section 9-9, fig. 4), this may be questioned when looking at figure 5. In fact, while section 11a (top central panel) clearly exhibits a continuous slab, the perpendicular sections show a gap of seismicity at different depths. Moreover, it is evident that the higher magnitude events are the deepest ones. A possible explanation of this remark is that the slab is continuous but has different rheological properties within its extension, as the tomography seems to suggest. Where the velocity is lower (due to petrological or thermal factors), seismicity is almost absent or at least less frequent. The magnitudes are also reduced, being the slab in a non perfectly-fragile condition in that portion.

- A completely different character is shown in the two investigated areas along the Apennines (north-central and northern). In both areas the depth and number of sub crustal earthquakes are comparable, the seismic activity being slightly higher in the former. The structure of the crust is also similar, the continental, thicker Adriatic-Padan crust (low heat flow) subducting beneath the transitional, thin peri-Tyrrhenian (high heat flow) type of crust (Mongelli et al., 1991). The sub crustal earthquakes are not deeper than about 100 km; the deep foci (fig. 3b) tend to concentrate beneath the bowed, broken line marking the edge of the over thrusting peri-Tyrrhenian Moho.

The northernmost investigated area is situated near the southern end of Western Alps (figs. 2 and 3b), close to the observed inversion of the over thrusting of the Moho boundary: in the Alpine range the external plate (European) is subducted beneath the Adria plate while, more eastwards, the latter domain is subducted beneath the peri-Tyrrhenian Moho. In this area, a small group of sub crustal earthquakes is positioned beneath this area of inversion. The correct position of these events, can be considered as not questionable, since Cattaneo et al., 1999 obtained a similar result analyzing the seismicity of the south-western Alps using a much denser seismic array and performing several location reliability tests. These events, which are not deeper than 60-70 km, even if according to Cattaneo et al., 1999, may reach 120 km depth, seem to be related to high velocity bodies (Scafidi et al., 2006) which are located in the Monferrato area. Several authors have investigated on the nature of these anomalous rocks, considering them as a part of a trapped mantle (Schmid et Kissling, 2000) or as portion of uplifted lower crust. These foci are very close to the region where the Bouguer anomalies (Klingelé et al., 1992) show an abrupt change and where it is supposed to be located a sudden variation of the Moho depth (see figures 8 and 1).

A meaningful complement to seismicity would derive from the analysis of focal mechanisms. However, such a study makes necessary a selection (on the basis, for example, of the magnitude of seismic events) of the data to display among the many fault plane solutions available for the peninsula, obtained either by first onset technique or waveform inversion. To avoid this arbitrary selection, we believe that a sort of cumulative representation suits best the investigation on large areas. In this sense, an useful aid is given by the comprehensive survey by Vannucci et al., 2004; they display a map representing the seismic deformation obtained by a moment tensor summation on a 0.5 degree per 0.5 degree. The narrow and continuous belt of extensional deformation runs from the Messina Strait to the Irpinia region and is also outlined by the extensional T-axes which are always perpendicular to the chain. The pattern of seismic deformation is less clear and more heterogeneous at the latitude of the Gargano promontory and northward, being mainly characterized by compressive deformation in the outer part of the chain and in the foredeep. The transition between the Southern and the Central Apennines is characterized by compressional and strike-slip focal mechanisms. However extension perpendicular to the mountain belt continues all the way to the Northern Apennines, as indicated by individual focal mechanisms and by P-axes of moment tensor sums.

To summarize, lateral heterogeneities, different thicknesses and a strongly irregular shape of the subducted Ionian-Adriatic lithosphere have produced a complex system of subduction in the Italian region. The two main arcs are characterized by the subduction of the oceanic lithosphere (Calabrian arc) and of continental lithosphere (north-central Apennines). In the area between the two arcs, the subduction process seems interrupted (Di Stefano et al., 1999, Spakman et Wortel, 2004); the distribution of focal mechanisms, above discussed, seems to strengthen this hypothesis. It is also remarked that in the southern Apennines, where the Moho overthrusting appears not bowed but tends to line up, no earthquakes are recorded in the upper mantle (fig. 3b). This could also support (Spakman et Wortel, 2004), the hypothesis of a progressive detachment northwards of the Calabrian slab.

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FIGURE CAPTIONS

1 – Summary of the seismicity in the Italian region according to the catalog by Chiarabba and al., 2005. All hypocenters recorded in the Italian region are projected on a NW-SE cross section. It is clear that the focal depth of the majority of the earthquakes is less than about 35 km . The foci slightly deepen while proceeding southwards. The areas where sub crustal events are observed are marked by numbers in the cross section: 1: western Alps, 2: north Apennines, 3: north-central Apennines, 4: SE Alps-Dinaric Alps, 5: Ionian-Aeolian slab.

2 – Distribution of magnitude versus depth for the seismicity in the Italian region, showing that the majority of the high M events (> 5) is recorded within the depth of about 30 km . The group of deep events (around 200 km) with M>5 is located along the Aeolian slab.

3 - Depth contour-lines of the Moho boundary (contour interval 2.5 km) and crustal domains (from Cassinis et al., 2003, modif.); the position of the cross sections described in this paper is also shown.
The empty rectangles represent the transects where the interpretation of the seismic structure is available (the numbers are the same used in Cassinis et al., 2003) while the grey filled rectangles correspond to the cross sections where only the earthquake hypocenters are shown. The foci contained in a volume of variable width (from 20 to 30 km) are projected on each cross section.
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 rft (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); 7: Fragmentation lines in the upper mantle; 8: Moho depth contour lines (km); 9: Moho depth contour-lines (subducted).

4 – The epicenters of the earthquakes according to the catalog by Chiarabba et al., 2005 plotted on the map of fig. 2.

a) Focal depth Z < 35 km

b) Focal depth Z > 35 km

The classes of magnitude are also indicated; white crosses are used for events whose magnitude is not computed.

5 – Interpretation of the DSS profile 9- 9 crossing the Tyrrhenian sea, the mainland of Calabria and reaching the Ionian sea. Numerical values indicate the velocities of P waves in km/s .The hypocenters, both in the crust and in the upper mantle, show the shape of the Ionian slab that is subducted north westwards beneath the Tyrrhenian sea; the onset of the subduction is clearly situated in the Moho step that marks the transition from the margin of the Ionian domain to the Tyrrhenian oceanic crust.

6 – a) Cross section 11a from the Aeolian islands to Calabria, the gulf of Taranto and to the tip of the Salentina Peninsula. Note the contrast between the SW part of the section (strong seismic activity beneath the Aeolian islands and Calabria (beginning of the slab) and the NE portion (continental type of crust belonging to the African plate) where the earthquakes are almost absent.

b) Cross sections directed perpendicularly to the 11a, showing the lateral continuation of the Aeolian slab. Note the gap in the slab at the depth of about 130 km (central section) and a minor gap at about 60 km in the southwestern section.

7 – a) Cross section 7-7 from Corsica to the Elba channel, south Tuscany, north central Apennines, Tiber valley and Adriatic coast near the city of Ancona, interpreted after the DSS data. The highest magnitude seismicity is concentrated in the upper crust, above the step of the Moho boundary near the city of Perugia (eastern side of the Apennines). The foci deepening westwards beneath the

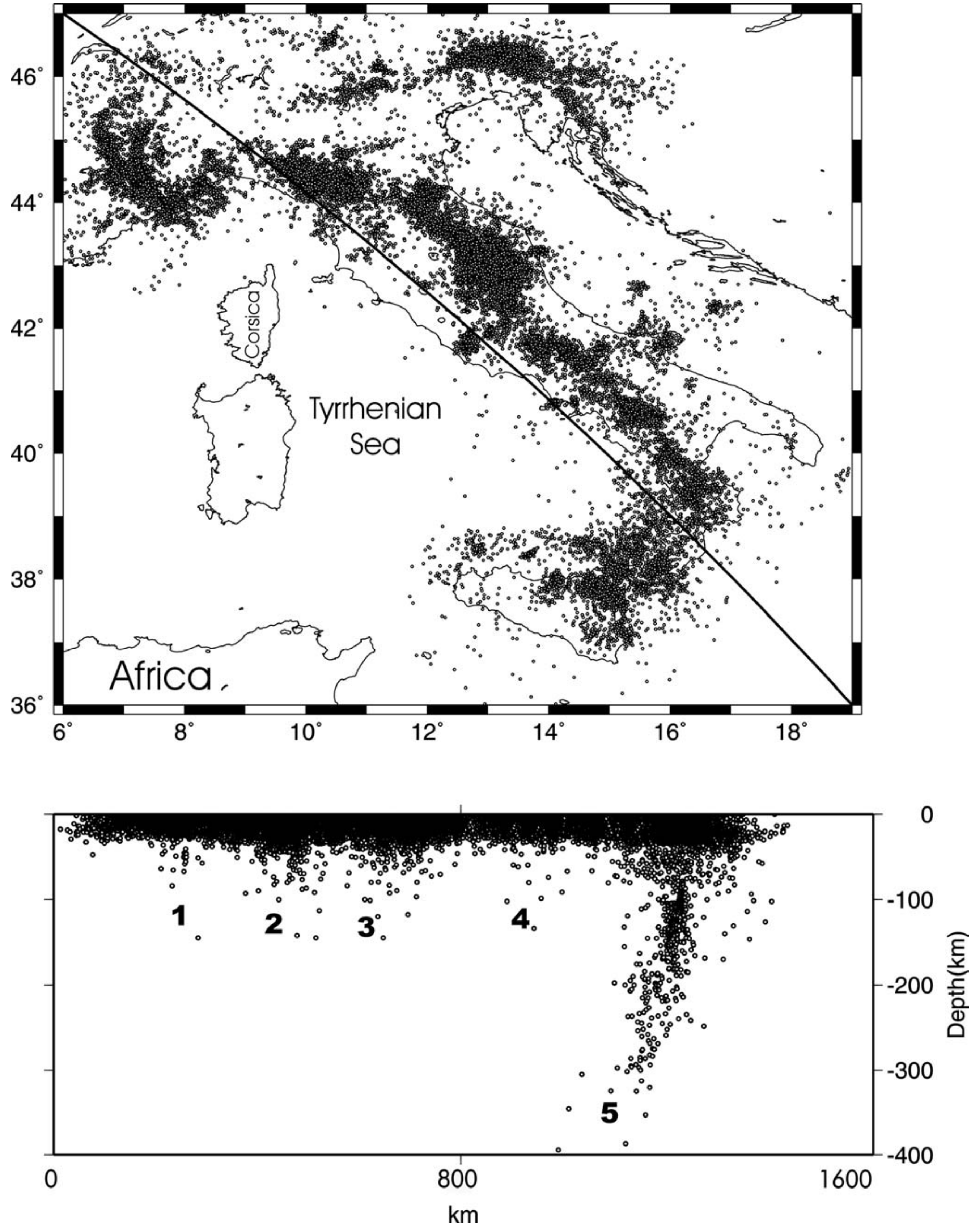
Adriatic coast seem to indicate the beginning of the subduction of the Adria microplate; the seismicity appears limited to the depth of about 80 – 90 km .

b) A line parallel to section 7-7 (about 80 km south) showing that the deep earthquakes have almost disappeared.

8 – a) DSS line 6-6 from the Ligurian sea north of Corsica to the coast of northern Tuscany near Viareggio, then crossing the northern Apennines. A moderate seismic activity is observed beneath the mountain range and a small group of deep foci (up to 80 km deep) is also shown.

b) The foci are plotted on sections perpendicular to line 6-6: no seismicity in the upper mantle is recorded beneath the Ligurian sea.

9 – Interpretative transects across the Western Alps. The central line 3-3 (from Grenoble to Turin and the Po valley) illustrates the crustal structure interpreted mainly after the DSS results. The interpretation of passive tomography in the crust and in the upper mantle (after Scafidi et al., 2006) is also shown in this section as well as in parallel sections (see the colour scale of P velocity in km/s). Note the group of sub crustal events along the southernmost c.s. Further comments in the text. The traces of cross sections are also plotted (see the enclosed map) on the Bouguer gravity anomalies (Klingelé et al., 1992)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Africa
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-400
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0
800
1600
km

Figure 1

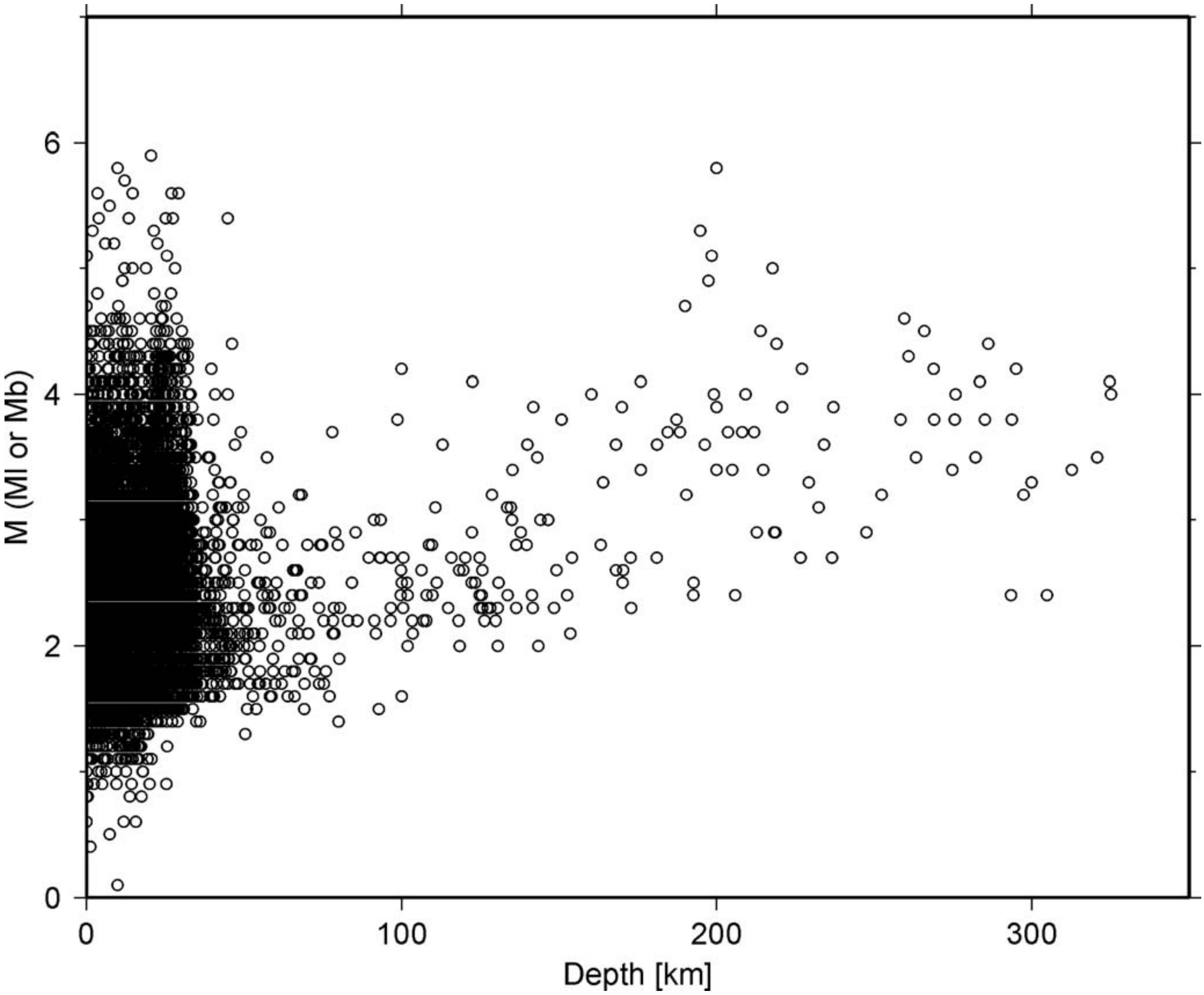


Figure 2

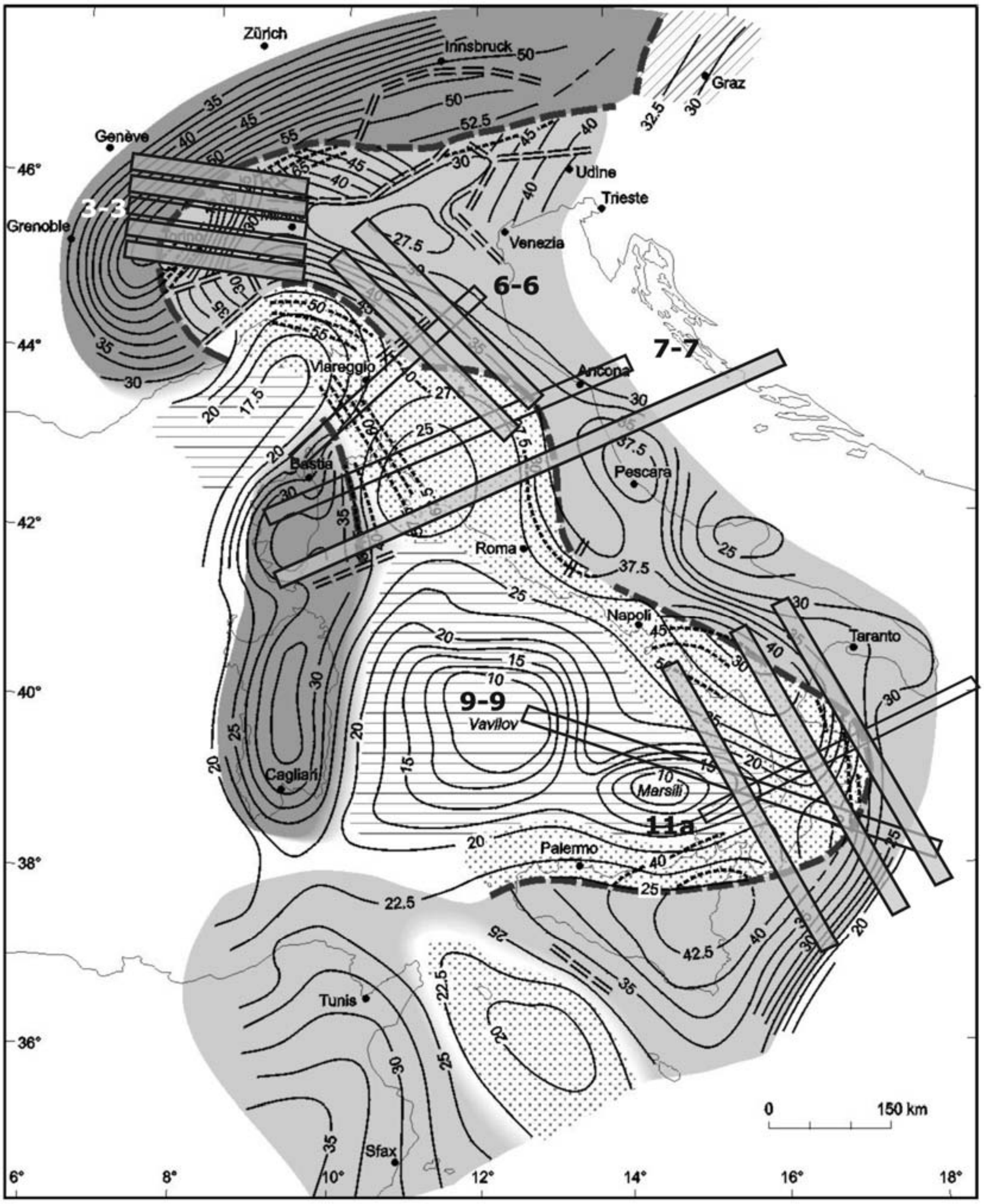

Zürich
Innsbruck
Graz
Genève
Grenoble
Udine
Trieste
Venezia
3-3
6-6
7-7
Viareggio
Ancona
Bastia
Pescara
Roma
Napoli
Taranto
9-9
Vavilov
Marsili
11a
Cagliari
Palermo
Tunis
Sfax
0
150 km
46°
44°
42°
40°
38°
36°
6°
8°
10°
12°
14°
16°
18°

Figure 3

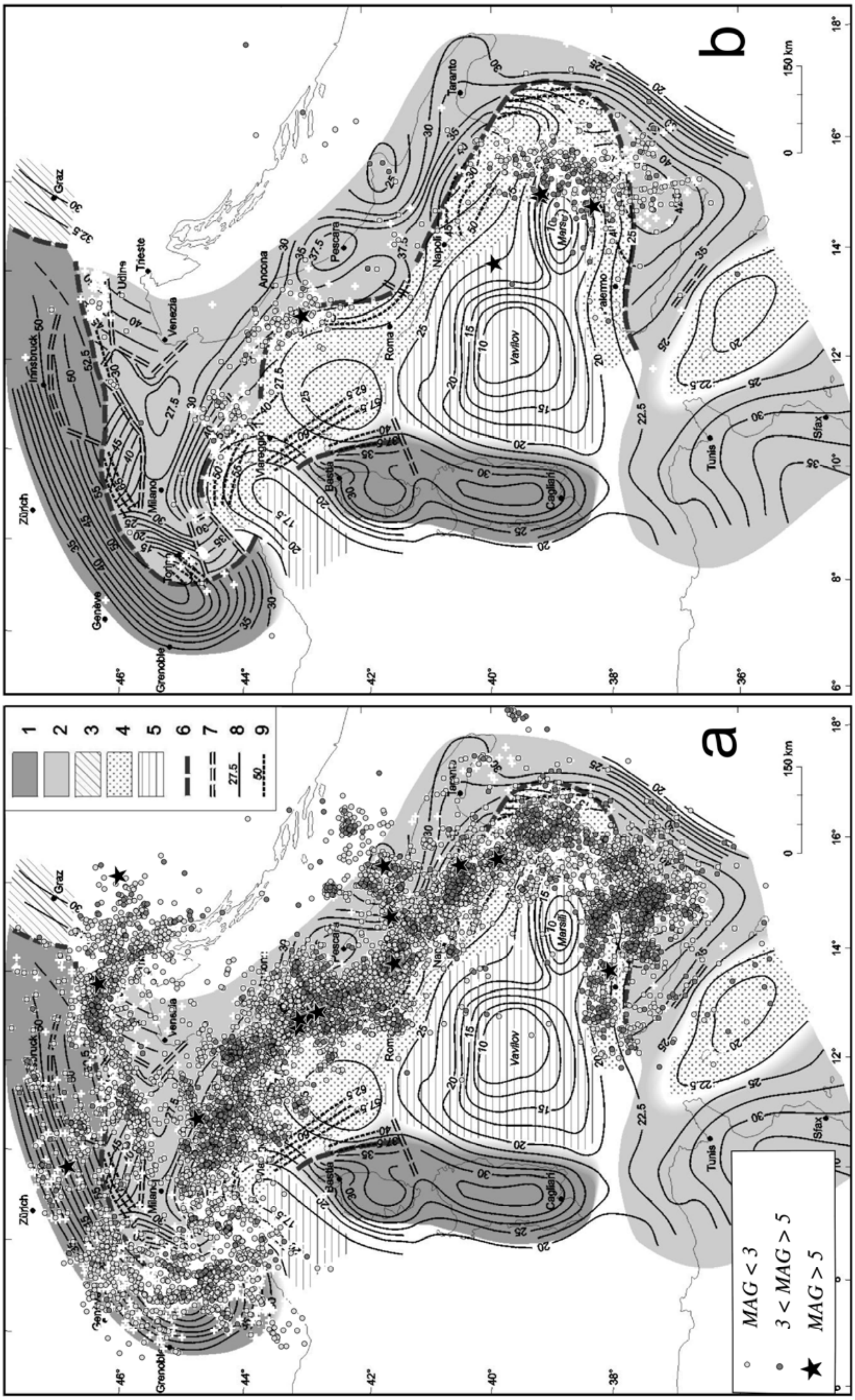

a
b
MAG < 3
3 < MAG > 5
MAG > 5
150 km
Zürich
Genève
Grenoble
Innsbruck
Graz
Milano
Torino
Venezia
Trieste
Udine
Ancona
Pescara
Roma
Napoli
Taranto
Bastia
Cagliari
Vavilov
Marsili
Palermo
Tunis
Sfax
Viareggio

Figure 4

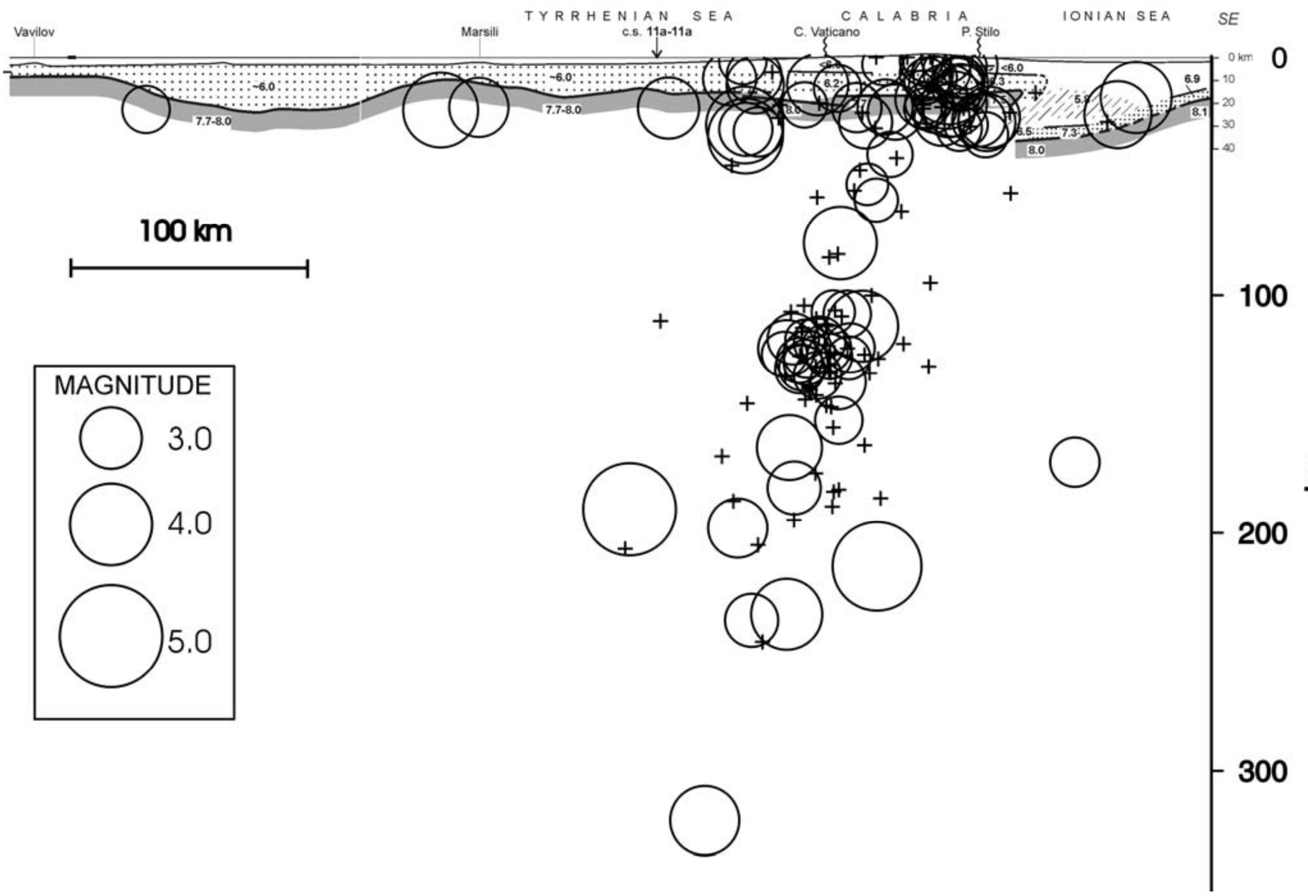
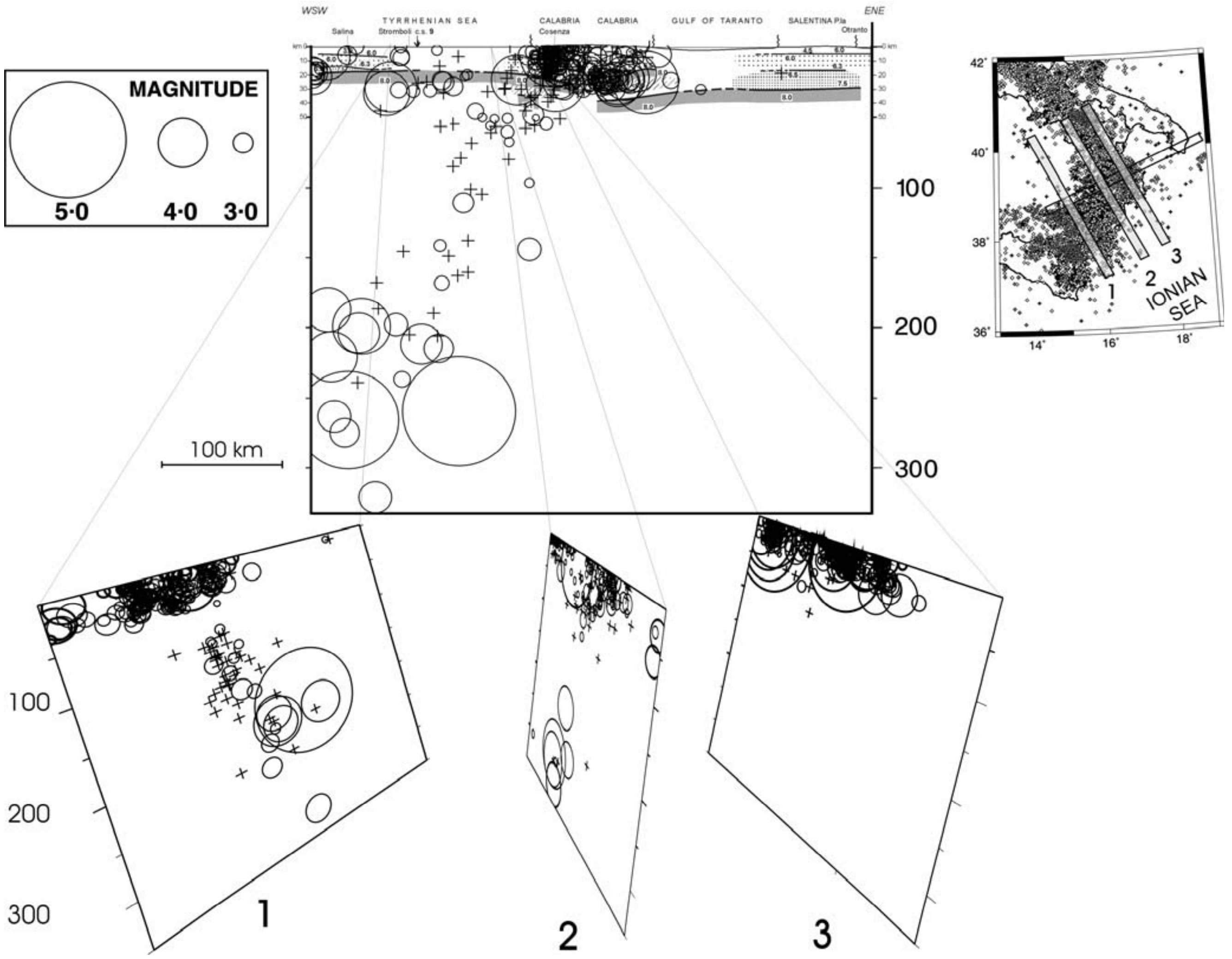

TYRRHENIAN SEA
CALABRIA
IONIAN SEA
SE
Vavilov
Marsili
c.s. 11a-11a
C. Vaticano
P. Stilo
100 km
MAGNITUDE
3.0
4.0
5.0
0
100
200
300
km

Figure 5



MAGNITUDE
5·0
4·0
3·0
WSW
ENE
TYRRHENIAN SEA
CALABRIA
CALABRIA
GULF OF TARANTO
SALENTINA P.la
Salina
Stromboli
Cosenza
Otranto
100 km
100
200
300
1
2
3
IONIAN SEA
42°
40°
38°
36°
14°
16°
18°

Figure 6

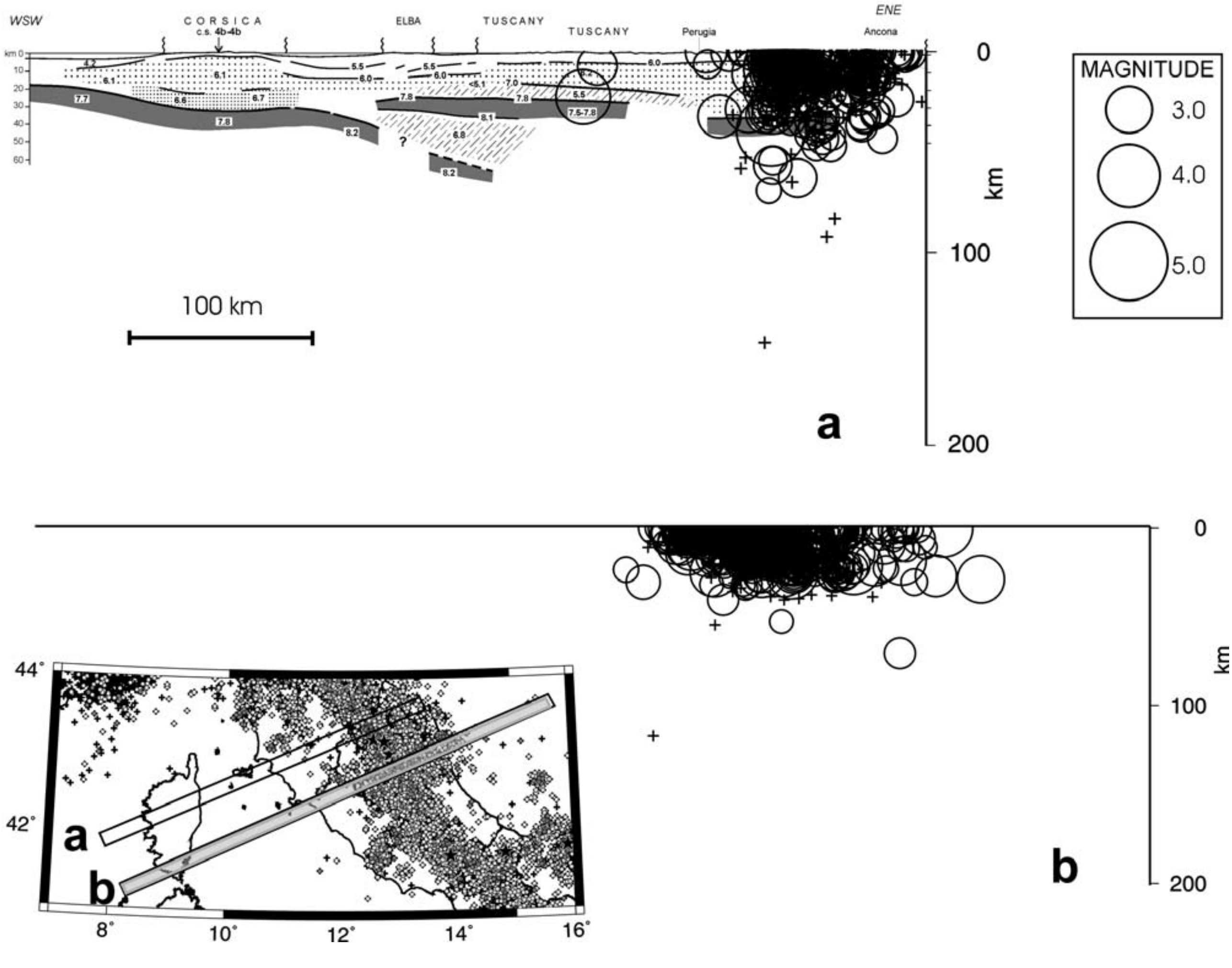
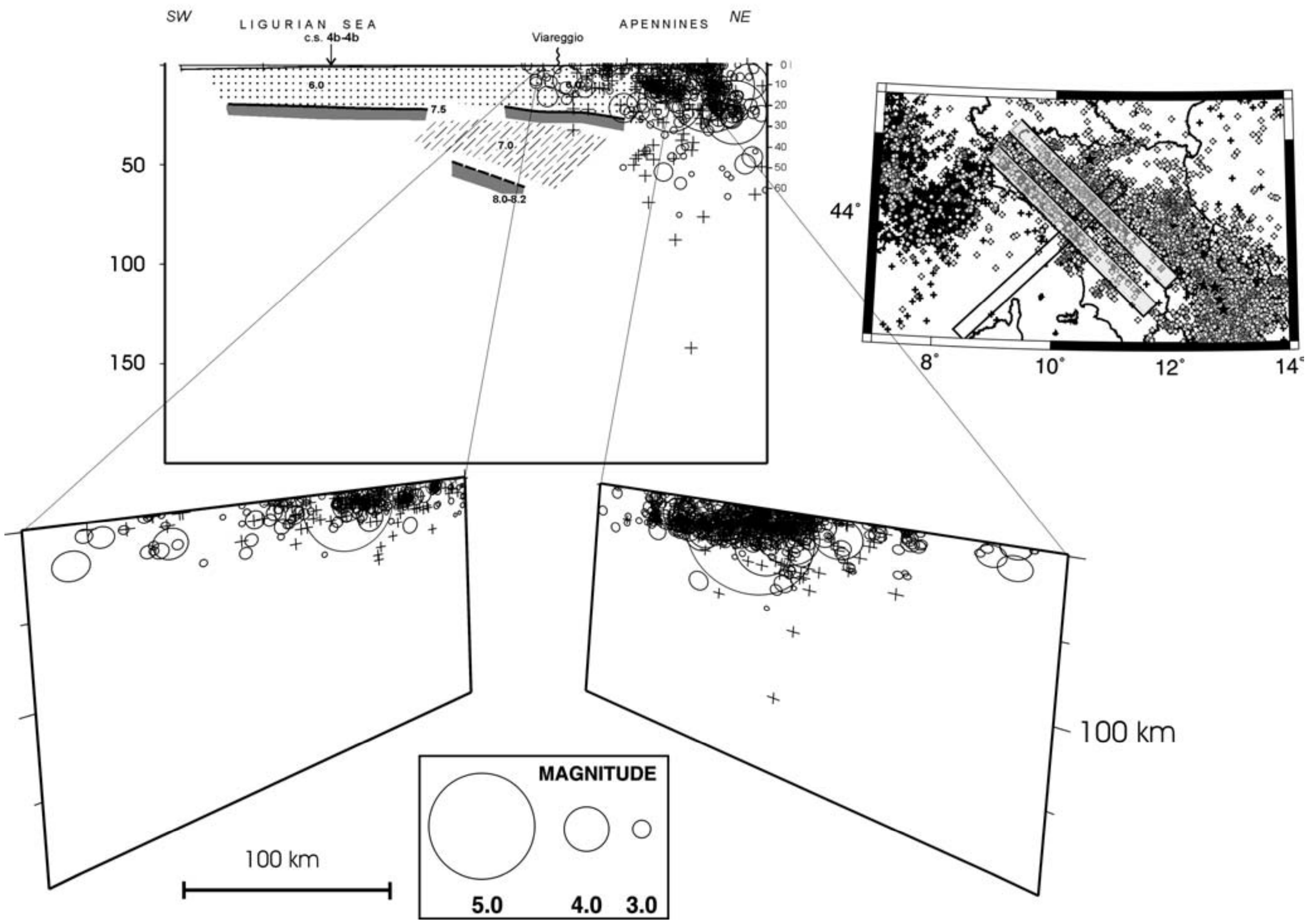
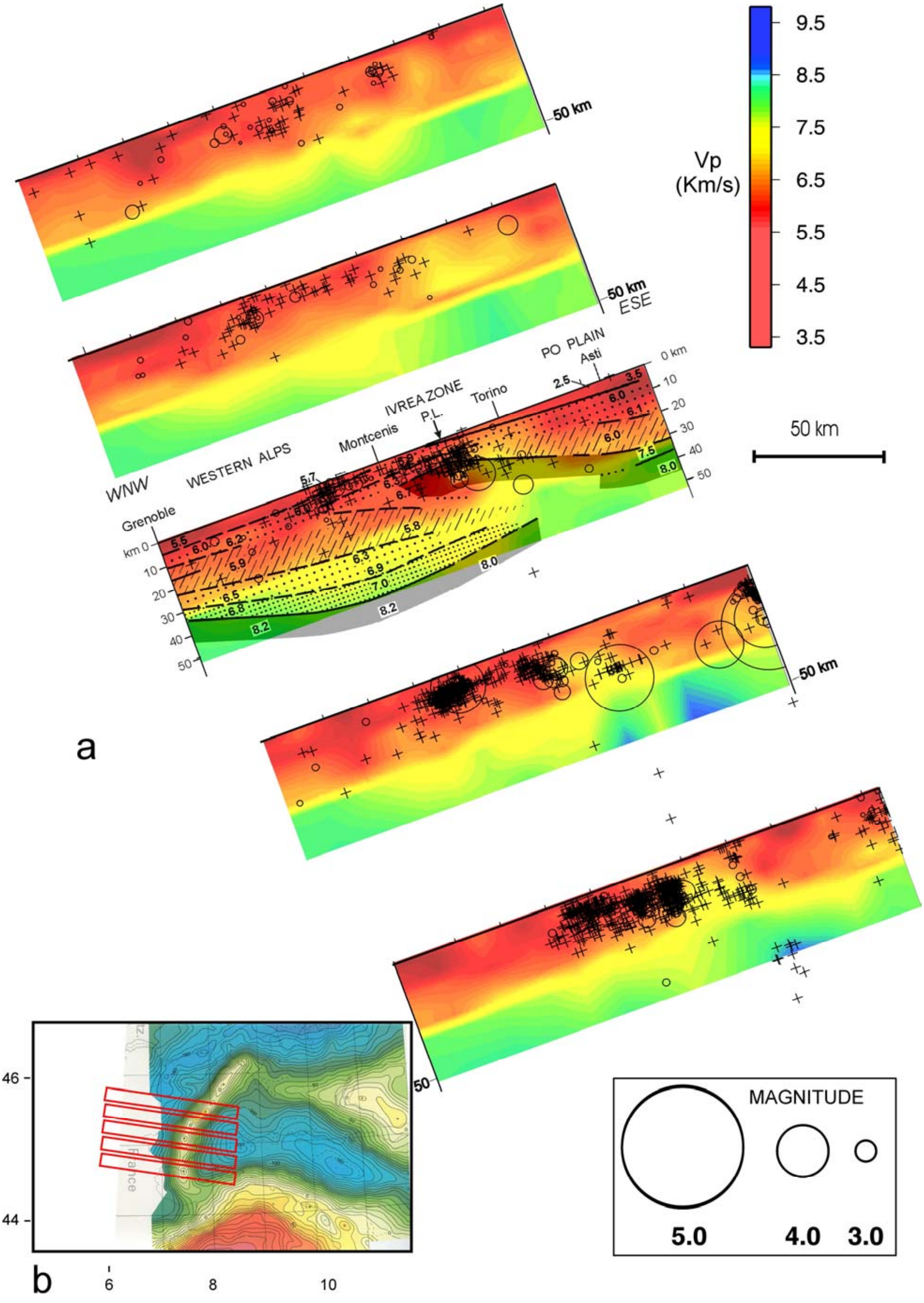

WSW
CORSICA
c.s. 4b-4b
ELBA
TUSCANY
TUSCANY
Perugia
ENE
Ancona
0
100
200
km
MAGNITUDE
3.0
4.0
5.0
100 km
a
0
100
200
km
b
44°
42°
a
b
8°
10°
12°
14°
16°

Figure 7



SW
LIGURIAN SEA
c.s. 4b-4b
Viareggio
APENNINES
NE
6.0
7.5
7.0
8.0-8.2
50
100
150
44°
8°
10°
12°
14°
100 km
MAGNITUDE
5.0
4.0
3.0
100 km

Figure 8



Vp
(Km/s)
9.5
8.5
7.5
6.5
5.5
4.5
3.5
50 km
50 km
50 km
ESE
WNW
WESTERN ALPS
Montcenis
IVREA ZONE
P.L.
Torino
PO PLAIN
Asti
Grenoble
a
MAGNITUDE
5.0
4.0
3.0
b
France
46
44
6
8
10

Figure 9