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# HypoDD relocated seismicity in northern Apennines (Italy) preceding the 2013 seismic unrest: seismotectonic implications for the Lunigiana-Garfagnana area

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***ABSTRACT*** We present the results of a study aimed at defining the geometry and kinematics of seismogenic volumes and structures of the Lunigiana-Garfagnana region (north-western Apennines) as depicted by background seismicity recorded before the seismic crisis of 2013. In this analysis we profited from earthquakes located with the high precision algorithm HypoDD and the availability of a large set of focal mechanisms. The obtained data set of well-located hypocentres allowed us to define some previously-unknown, or only poorly-defined, geometric characteristics. We also confirmed, with a finer detail, some already-known first order features such as the presence of two NW-SE-trending zones of seismicity, west and east of the Apennine water divide, separated by a low seismicity corridor. The main findings of this study are: 1) most of the seismicity of the western zone is located in the Lunigiana graben, north-NW of the Apuane Alps; 2) at depth, the Lunigiana seismicity deepens to the east parallel to the top of the basement, which in turn coincides with an extensional detachment (~30° E-dipping); and 3) the Lunigiana seismicity terminates southwards with a dense cluster of epicentres oriented nearly E-W, parallel to the transfer fault zone that delimits the Apuane Alps to the north; south of this cluster, a strong reduction of seismicity is observed and the locations are shifted to the eastern sector. These findings might help in interpreting the seismotectonics of the 1481, 1837, 1920 and 1995 earthquakes, all located within the E-W-trending cluster at the southern termination of the Lunigiana seismicity.

**Key words:** seismicity, high-precision location, focal mechanisms, northern Apennines.

## 1. Introduction

The western side of the northern Apennines has been struck in the previous centuries by several medium to high magnitude earthquakes (Solarino, 2005), among which the 1481 ($M_S$=5.9), the 1834 ($M_S$=5.6), the 1837 ($M_S$=6.4) and the 1920 ($M_S$=6.5) (Camassi and Stucchi, 1997) are certainly the most relevant (Fig. 1). The location of these events, which does not include the depth, is known with the confidence typical of macroseismic data except for the 1920 event, located with instrumental data (Solarino, 2005) and for which a constraint on the depth is available.

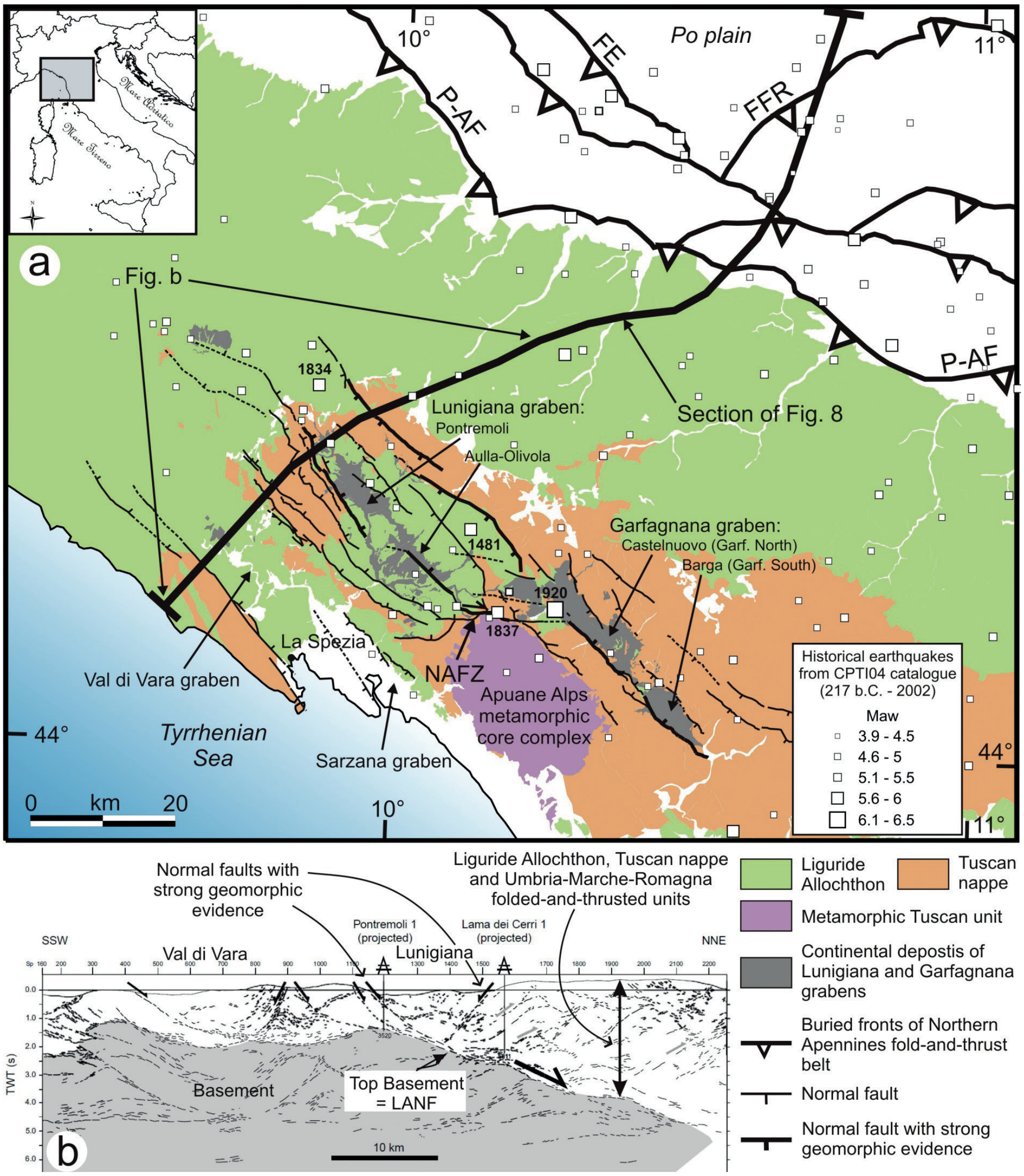

Fig. 1 - a) Schematic tectonic map of northern Apennines from the Lunigiana – Garfagnana grabens to the fronts of the Apennines fold-and-thrust belt buried beneath the Po plain. Faults of the Lunigiana-Garfagnana area are from Di Naccio *et al*. (2013); thrust fronts are from 1:500,000 Structural Model of Italy (Bigi *et al*., 1990). P-AF = Pede-Apennine thrust front; FE = thrust front of the Emilia folds; FFR = thrust front of the Ferrara – Romagna folds; NAFZ = North Apuane normal-oblique right-lateral Fault Zone (i.e., transfer zone between Lunigiana and Garfagnana grabens). b) Partially interpreted line drawing of a seismic line crossing the Lunigiana graben [in seconds T.W.T.; from Argnani *et al*. (2003) slightly modified].

Since 1920, the area has been characterized by a multitude of low magnitude events sometimes interrupted by 4 to 5 $M_L$ events (in 1928, 1939 and 1995) until the recent seismic crisis that interested the area in 2013, when a 4.8 and a 5.2 $M_L$ events shook the area. The occurrence of earthquakes motivated in the late 1990s the establishment of a steady seismic monitoring of the area, which was accomplished starting from 1999 (Solarino *et al*., 2002a).

The recent seismicity of the whole northern Apennines is compiled in a comprehensive database which holds many hundreds of events and it is known at either a global (De Luca *et al.*, 2009) and local scale (Solarino *et al.*, 2002a, 2002b). However, the link of the major seismicity to the tectonic lines is not completely understood and especially the occurrence of the minor events is still under debate for what regards the causative seismogenic structures. The existence of a rather complex fault system in the Lunigiana-Garfagnana area is in fact acknowledged and somewhat mapped, but little is known about its extension and seismotectonic character.

In this work we present original results obtained applying a high precision location algorithm, namely HypoDD (Waldhauser and Ellsworth, 2000) to a selected and re-picked data set to increase the accuracy in the determination of the seismic locations; a seismotectonic analysis is then conducted using a data set of focal mechanisms. The joined results are used to possibly constrain the geometry, shape, size and extension with depth of seismogenic volumes and structures of this complex sector of the Apennines.

## 2. Tectonic setting of the Lunigiana-Garfagnana area

The Lunigiana - Garfagnana area is located at the north-western termination of the Apennines of Italy, west of the Apennine water divide, and it is characterized by a 80-km long NW-SE-oriented system of extensional structures (Lunigiana and Garfagnana grabens in the literature) which dissect the contractional structures of the Apennine orogeny (Fig. 1). The contractional structure is a NW-SE-trending belt formed by NE-verging tectonic units stacked since the Late Oligocene, after the collision of the Corsica-Sardinia and Adria continental blocks [for a comprehensive synthesis and review see. Lavecchia (1988), Bortolotti *et al.* (2001), Carmignani *et al.* (2001), Castellarin (2001), Vai (2001), and references therein]. Starting from the Late Miocene, the area was affected by large-scale extensional tectonics which produced, mostly through low-angle normal faults, the opening of the Tyrrhenian Sea, the exhumation of the deep metamorphic units (e.g., the Apuane Alps) and the formation of NW-SE-striking grabens filled by marine, marine-to-continental or continental (eastern grabens) sedimentary successions, progressively younger to the east [see Argnani *et al.* (2003), Brozzetti *et al.* (2009) and references therein for a review]. In the northernmost Apennines, the Lunigiana-Garfagnana grabens, are the easternmost structures of the stretched Apennine crust.

The Lunigiana graben extends from Pontremoli to the northern side of the Apuane Alps, along the upper Magra River valley, for a total length of ~45 km (Fig. 1). By considering the distribution of continental deposits, the Pontremoli and Aulla-Olivola sub-basins can be distinguished. The Garfagnana graben is located more to the SE, and extends for ~27 km along the Serchio River valley, parallel to the eastern margin of the Apuane metamorphic core. Again, two sub-basins can be recognized (Castelnuovo and Barga). The Mt. Picchiara – Mt. Cornoviglio horst and the Apuane metamorphic core separate the Lunigiana and Garfagnana grabens from two western, nearly parallel grabens: the Val di Vara – La Spezia and Sarzana grabens.

The presence of NE-dipping normal faults along the western side of the Lunigiana and Garfagnana grabens and SW-dipping normal faults along the eastern side has been recognized since a long time (Elter *et al.*, 1975; Eva *et al.*, 1978; Bartolini *et al.*, 1982; Raggi, 1985; Carmignani and Kligfield, 1990; Bernini *et al.*, 1991; Bernini and Papani, 2002).

The easternmost NE-dipping faults (i.e., the faults closest to the graben axis) and some of the major SW-dipping faults are characterized by strong geomorphic evidence and were considered as late Quaternary, possibly active, normal faults by Di Naccio *et al.* (2013) on the basis of a morphotectonic analysis from channel longitudinal profiles crossing the faults (e.g., knickpoints) coupled with basic geologic data (e.g., geologic maps and sections Fig. 1). Between the southern termination of the Lunigiana graben and the northern termination of the Garfagnana graben, there is a nearly E-W-striking, N-dipping fault zone with normal-oblique right-later kinematics. This fault zone delimits to the north the Apuane metamorphic core and was interpreted as a presently active transfer fault between the Lunigiana and Garfagnana extensional grabens [North Apuane Transfer Zone; Brozzetti *et al.* (2007)].

Subsurface data from seismic reflection profiles indicate that the extension is asymmetric, with a NE-dipping low-angle normal fault from which high-angle NE-dipping synthetic and SW-dipping antithetic normal faults are splaying (Carmignani and Kligfield, 1990; Artoni *et al.*, 1992; Camurri *et al.*, 2001; Argnani *et al.*, 2003) (Fig. 1b). In the interpreted seismic line of Fig. 1b (from Argnani *et al.*, 2003), the low-angle normal fault (LANF hereinafter) corresponds to the top of the basement and deepens at ~30° up to depths of 4.5-5.0 s TWT (~12-15 km).

The epicentres of the historical earthquakes are mostly located within the Lunigiana and Garfagnana grabens (Fig. 1a). This observation together with the focal mechanisms available up to now (e.g., Frepoli and Amato, 1997, 2000; Solarino *et al.*, 2002b; Eva *et al.*, 2005; Pondrelli *et al.*, 2006), and the strong geomorphic evidence along the Lunigiana-Garfagnana normal fault system (Di Naccio *et al.*, 2013) suggest that an extensional tectonics is presently active.

Nevertheless, the present activity and seismogenic role of the NE-dipping LANF is still a matter of debate.

## 3. The seismic network and data analysis

As known, the spatial and temporal distribution of earthquakes provide information on the tectonic regime and the material properties of an area, and on the depth of the brittle-ductile transition. Precise earthquake hypocentre locations are therefore essential requirement to study structures and processes that trigger seismic activity. The accuracy of hypocentre locations must be of the same order of the size of the structures under study, and it depends on several factors. The most important are the number and type of available seismic phases recorded at the seismometers, the accuracy with which arrival times are measured, the network geometry, the knowledge of the crustal velocity structure and the linear approximation to a set of nonlinear equations, which is assumed in the location process.

The existence of many reliable data accounts for the first three quoted requirements, that is number and quality of available seismic phases and network geometry; for this reason a careful inventory and merging of all available seismograms have been carried out.

The seismicity of the study area is under constant monitoring by the national seismic network (National Central Seismic Network, Istituto Nazionale di Geofisica e Vulcanologia, RSNC hereinafter) and by a pool of local stations belonging to a regional network [RSLG – Regional Seismic network of Lunigiana and Garfagnana, a branch of the Regional Seismic Network of Northwestern Italy (Eva *et al.*, 2010; Solarino *et al.*, 2002a)], able to well record

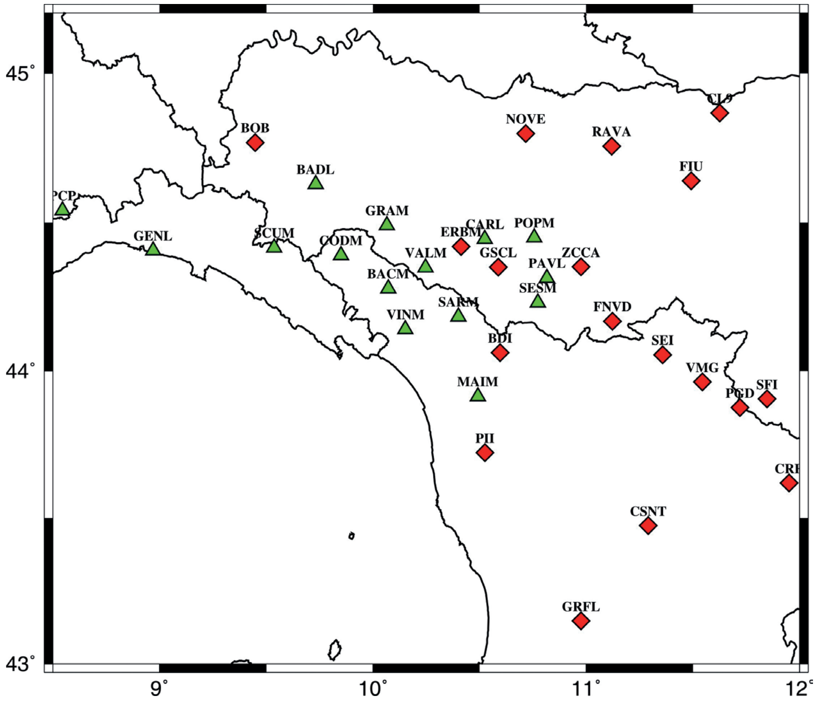

Fig. 2 - Location of the seismic station used in this work. In green the stations belonging to the RSLG (Regional Seismic Network of Lunigiana and Garfagnana), a branch of the Regional Seismic Network of North-western Italy. In red stations of the RSNC (Rete Sismica Nazionale Centralizzata).

also lower magnitude seismicity. These latter seismic stations almost surround the area of the Lunigiana – Garfagnana (Solarino *et al.*, 2002a; Ferretti *et al.*, 2005) and, as a consequence of the small inter-distance between instruments, location of the events that occur within the network are highly accurate. On the other hand, the quality of the location for events occurring outside the RSLG network would be much less reliable if the data were not supplemented by the seismic signals of the stations of the RSNC (Eva *et al.*, 2005). Fig. 2 shows a frame of the stations that operated in the study area and used in the present work.

Here we take into account the data for the period 1999 - 2011 in order to profit from the best instrument geometry as the RSLG seismic network became fully operative at the beginning of that decade (Solarino *et al.*, 2002a). The selection of data, in the area 43° 30’ N – 45° 00’ N and 9° 00’ E – 11° 30’ E, is made on the basis of number of phase readings (at least 10 P+S): the resulting data set, made of about 1200 earthquakes, has been first merged with the seismograms collected at the RSNC stations in an unique data set of about 80,000 three-component waveforms. Afterwards, the seismograms were carefully revised by a complete manual phase picking to guarantee as low as possible errors in the input data and to ensure a consistent attribution of weight to the readings. We obtained a catalogue of about 21,000 P and 12,000 S-wave pickings. To take into account the likely differences introduced by the data revision, all data were used to relocate the earthquakes with a standard technique (Lahr, 1980, 1984, 1999) and a routine velocity model. The results are shown in Fig. 3.

Starting from the idea that the improvement in the locations, of around 10-12%, due to the increased number of data can be significantly enhanced by the choice of an adapt location

| Depth | Velocity P |
|---|---|
| 0.0 | 3.80 |
| 1.0 | 4.00 |
| 2.0 | 4.40 |
| 4.0 | 5.40 |
| 10.0 | 6.03 |
| 13.0 | 6.17 |
| 18.0 | 6.44 |
| 23.0 | 6.51 |
| 33.0 | 8.10 |

Table 1 - 1-D velocity model used in this work.

algorithm, we applied the double difference relocation technique (HypoDD hereinafter) of Waldhauser and Ellsworth (2000).

A detailed description of the methodology is beyond the scope of this paper, therefore only a brief summary of the basics and main features is given. In HypoDD the residuals between observed and theoretical travel-time differences are minimized for pairs of earthquakes at each station and the spatial offset between these events can be computed with high accuracy. The location method incorporates ordinary absolute travel-time measurements and/or cross correlation P and S wave differential travel-time measurements. In our study, we could profit from a compromise between the number of cross-correlations and travel-time data. However, as it will be discussed in the next paragraphs, we experienced a diminution of locatable events. We believe that such a situation is partly due to the complex history of the networks operating in the northern Apennines.

The cross-correlations were computed for stations at distances of up to 100 km from the centre of the selected area. A greater distance has been taken into account for the catalogue data. Travel time differences were predicted using the 1-D layered velocity model computed for the tomographic inversion described in Scafidi and Solarino (2012). This model was obtained by series of simultaneous inversions of 1-D velocities, hypocentre locations and station corrections using the software "Velest" (Kissling, 1988). Since the methodology is a trial and error process using different layering and velocities as initial guesses, many sets of parameters, based on results from previous studies in this area (Cattaneo *et al.*, 1986; Makris *et al.*, 1999, Scafidi *et al.*, 2006), have been used in the search for the more appropriate starting reference model. The best-obtained model (Table 1) provides an improvement of about 52% in the data variance and 31% in the rms (root mean square) of the residuals, compared to the initial model. The best fitting velocity model has a Vp/Vs ratio of 1.70 and a Moho at 33 km depth.

Although, the structure of the NW Apennines is very complex and difficult to depict with a 1D model only; this choice seems to be appropriate because the DD algorithm is a relative earthquake location method and is, then, much less dependent on the velocity models, compared with "absolute" methods (Waldhauser and Ellsworth, 2000). The number of relocated events after the application of the HypoDD algorithm is decreased down to 805 earthquakes (about -70% of the initial amount). The location errors are typically one to two orders smaller compared to the best quality catalogue data. In fact, 93% of the relocated earthquakes show errors less than 1.5 km with a sensible improvement with respect to the original locations (where only 25% matched this threshold). It must be underlined that HypoDD allows two options to solve the system of equations: singular value decomposition (SVD) and the conjugate gradients method [LSQR: Paige and Saunders (1982)]. SVD is useful for examining the behaviour of small systems as it provides information on the resolvability of the hypocentral parameters and the amount of information supplied by the data, and adequately represents least squares errors by computing proper covariances. LSQR takes advantage of the sparseness of the system of DD-equations being able to efficiently solve a large system. Errors reported by LSQR, however, are grossly underestimated and need to be assessed independently. In our case the location has been performed using LSQR due to the amount of data to be processed. A full comparison of the performances of the DD algorithm on the whole data set with the two solving schemes is not possible because the size and burden of the inversion problem are not compatible with the numerical capability of standard computers. However, few tests on limited subsets, of size compatible with the best available computing capacities, were conducted to compare the errors in either cases. It turns out that the errors are randomly distributed, although on average SVD provides an increase of about 30-35% with more evident differences on the estimate of depth, LSQR locates more (some 25 to 30%) events and there is a bias in considering a smaller database because the number of cross-correlations diminishes making very difficult to estimate which is the contribution of the varied algorithm and which is instead due to the decreased number of data.

In the rest of the paper the LSQR locations will be taken into account as, having considered only the best located events, the usage of SVD does not significantly change the quality of the locations while LSQR ensures the optimum constrains on the data and the maximum number of them with a comparable reliability.

## 4. Results: cross sections and focal mechanisms

The relocated seismicity is displayed in Fig. 4, where it overlays a map of the faults of the northern Apennines (see Fig. 1a). The faults drawn in green are those characterized by strong geomorphic evidence, and considered probably active by Di Naccio *et al.* (2013). The grey boxes indicate the seismogenic sources proposed in the DISS 3.1 database (DISS Working Group, 2010), named from, NW to SE, as “Pontremoli”, “Aulla”, “Garfagnana North” and “Garfagna South” sources. The coloured stars show the position of the 1481, 1837, 1920, and 1995 earthquakes.

As expected, the relocated events appear more clustered than the initial distribution (compare Fig. 3 with Fig. 4). A diminution of number of total events is clearly evident, concurring to the more grouped appearance.

At a first glance, the seismicity seems to highlight two separate zones, west or just close to the Apennine water divide and east of it. The distinction between the two sectors is a very narrow aseismic band, located slightly east of the water divide, which acts as a corridor between the two sectors. Such an area is well visible when relocated events are displayed as equally sized circles, however this feature is also evident in Fig. 4 and confirms previous studies by Solarino *et al.* (2002a, 2002b).

The seismicity of the western sector is interrupted, southwards in the Lunigiana graben, by a nearly E-W-trending alignment of seismic events close to the northern termination of the Apuane Alps metamorphic core. The northern termination of the Apuane Alps

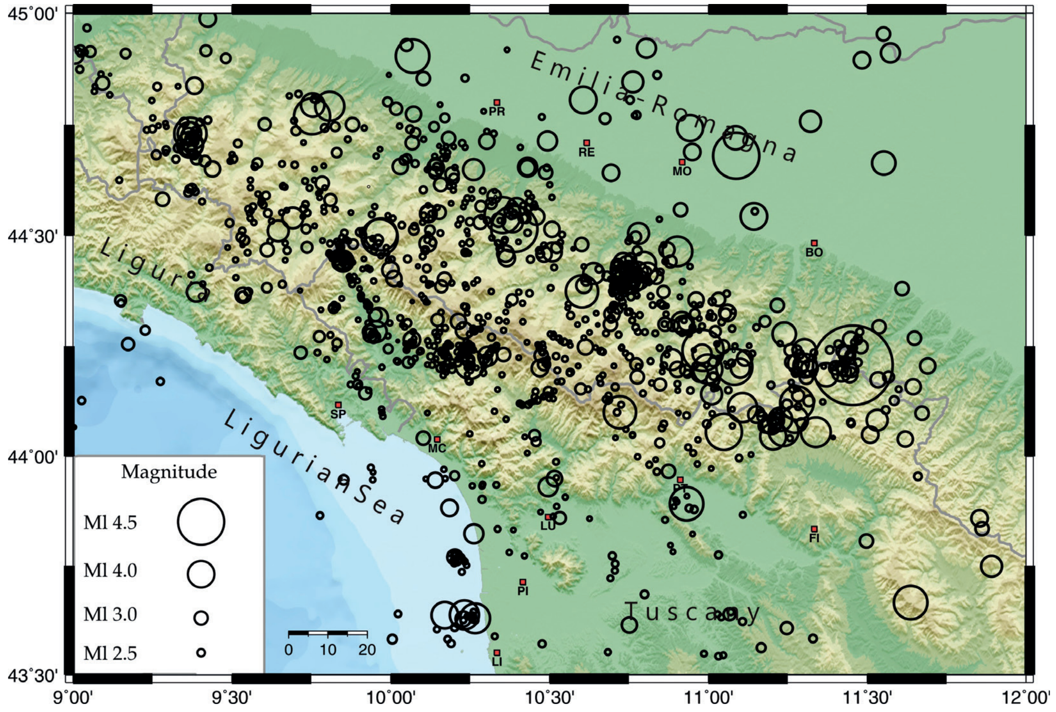

Fig. 3 - Preliminary hypocentral distribution of the data set used in this work as obtained with the “standard” Hypo (Lahr, 1980, 1984, 1999) technique.

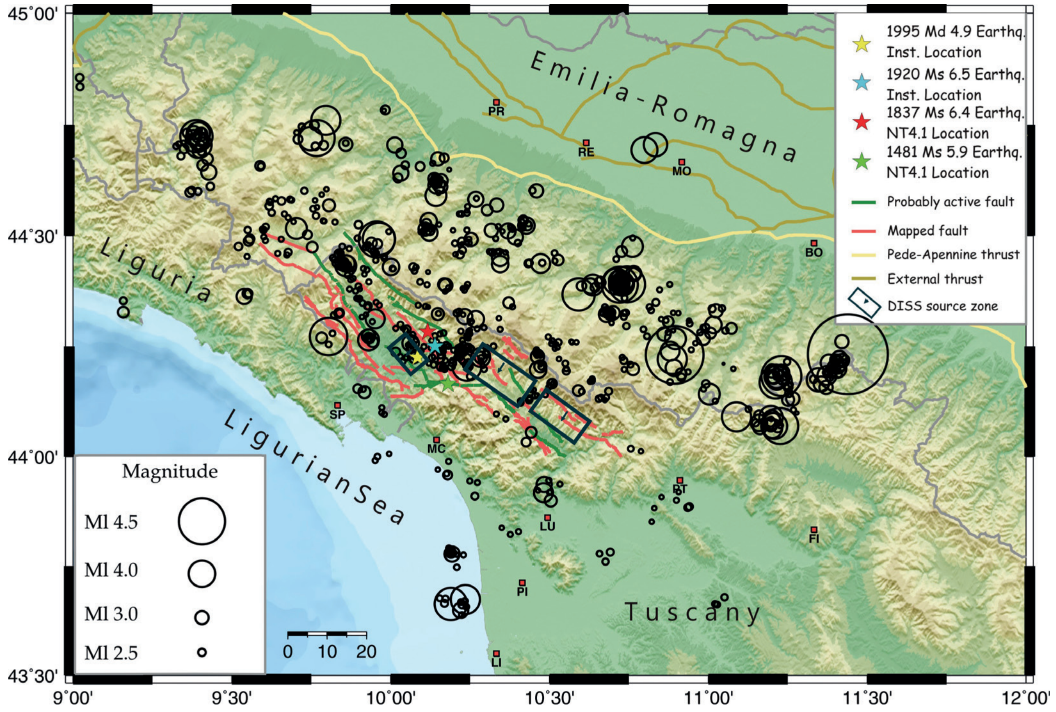

Fig. 4 - Relocated seismicity. The main historical events, the mapped faults (from Di Naccio et al., 2013) and the seismogenic sources from the DISS 3.1 database (DISS Working Group, 2010) of the Lunigiana-Garfagnana area are also shown.

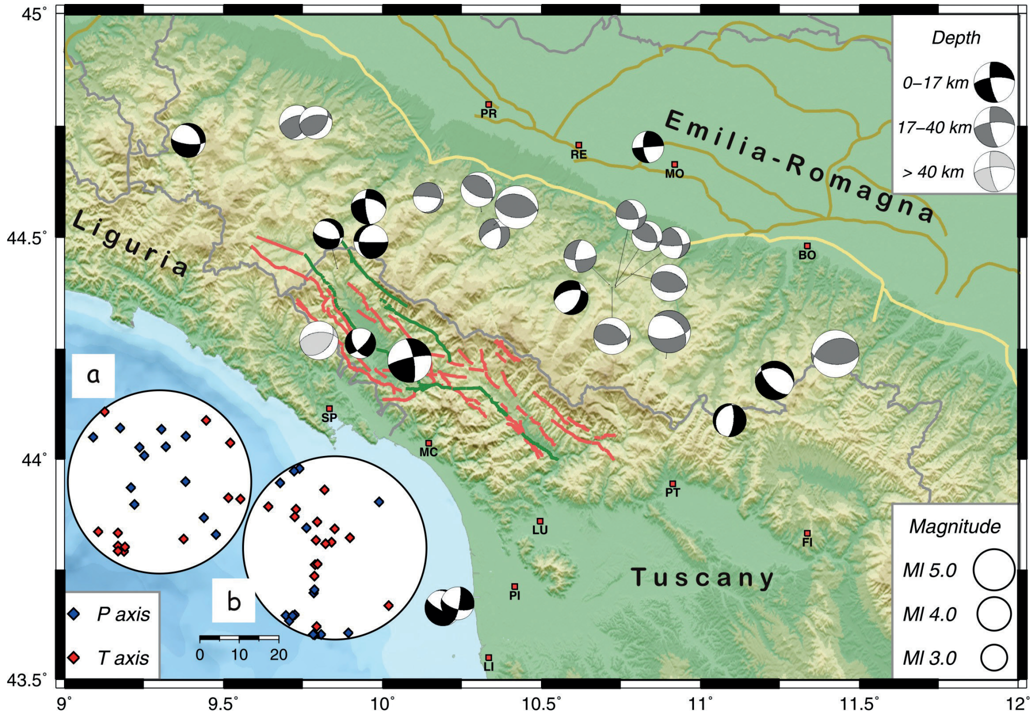

Fig. 5 - Focal mechanisms for the area under study. Shallow (1-17 km depth) events in black, deep events (> 17 km) in grey. The mapped faults for the area are also shown (for description see Fig. 4). The inlays display the distribution of P and T axes; a) layer 0-17 km b) depth > 17.

corresponds to the right-lateral normal-oblique North Apuane transfer fault zone, striking on average E-W and dipping to the north [NAFZ in Fig. 1a; Brozzetti *et al.* (2007)]. Therefore, the seismicity seems to be confined southwards by the NAFZ, which might play an important role in controlling the earthquake distribution of the area. It is interesting to note that the strongest historical earthquakes (coloured stars in Fig. 4) locate within the E-W-trending belt of seismicity just to the north of the NAFZ. Going S-SE-ward from this latter seismic zone, the seismic activity significantly decreases, with no earthquakes within the Garfagnana North and South sub-grabens and only few epicentres in between or NE of them.

In the eastern sector the higher magnitude events for the period under study are located; events are more clustered and tend to organize in SW-NE oriented alignments. Seismicity interrupts southwards of the area where the highest magnitude events took place [i.e., Monghidoro sequence, 2003: Piccinini *et al.* (2006)].

In Fig. 5 the focal mechanisms for events with magnitude greater than 3.5 are displayed. A different colour of the beach balls is used for shallow and deeper mechanisms. The data have been extracted either from an existing database (Eva *et al.*, 2005) and re-computed introducing the new location or taken from the RCMT catalogue (Pondrelli *et al.*, 2006). The distribution of the focal mechanisms is not homogeneous but an oblique component is generally evident. In principle, the orientation of the nodal planes varies from Appeninic (around N150°), for the normal and thrust focal solutions, to anti-Apenninic, for the strike-slip mechanisms. More in details, the focal solutions show different trends in the layers above and below 17 km depth. The inlay of Fig. 5, displaying the distribution of P and T axes for the two layers (0-17, >

17 km), clearly shows that in the shallow layer the P axes are more vertical with respect to the T axes while in the deeper layer it is conversely. More in details, in the layer 0-17 km only pure strike-slip and transtensional mechanisms are located, while at greater depth the transpressional component prevails. In the latter case the SW oriented nodal planes corresponds to the geometric features of the Apenninic thrust. It is noteworthy that the distribution of focal mechanisms for this area led many authors (e.g., Lavecchia, 1988; Bigi *el al.*, 1990; Frepoli and Amato, 1997) to assert a transition from extensional to compressional regime, which instead can be interpreted as a superposition of different kinematic layers.

With the aim to shed some light on the area, a number of SW-NE-oriented seismicity cross-sections have been drawn, and are shown in Fig. 6. The three northern sections are very alike, while the southern ones show different features. The cross-sections A-B, C-D and E-F show that in the western zone the seismicity is shallower and it deepens toward east down to about 20 km. In the eastern zone, instead, there is almost no seismicity near the surface and the hypocentres are concentrated between 15 and 30 km depths. The distinct behaviour of these two zones is clearly remarkable in all the three cross-sections, that show, from west to east, an alignment dipping 30° that becomes almost horizontal at about 25 km depth. It is noteworthy that the aseismic area mentioned before lays in between the two zones. In the western part, this alignment is very shallow, and approaches the ground surface close to the western border of the Lunigiana graben. The shallow cluster of events in section E-F is located where the historical strongest events (1481, 1837 and 1920) occurred.

For what concerns the southern cross-sections, in I-L and M-N the seismicity is shallow (less than 10 km). In section G-H two high-angle alignments are visible. The westward alignment only deepens to less than 20 km and seems to dip at high-angle to the NE. The eastern alignment goes down to 30 km depth. The dip of this latter alignment is not clear, though a high-angle NE-dip can be inferred, at least for the shallower portion (15-25 km).

The NW-SE-oriented cross-sections, displayed in Fig. 7, are drawn respectively west (O-P) and east (Q-R) of the Apennine water divide. The first one shows a band of seismicity confined within the shallower 20 km depth, with a reduction of the number of events close to the Apuane Alps. Just north of the Apuane Alps, a high concentration of seismicity is remarked and the major earthquakes of 1481, 1837 and 1920 occurred. In this zone also the 1995 event occurred, at a depth of 8 km and with an almost pure strike-slip focal solution. Finally, a seismic gap is clearly visible in the range 25 to 50 km depth and only few events are located at a depth greater than 50 km, in the central-southern part of the cross-section.

The eastern cross section (Q-R) shows seismicity along a nearly horizontal alignment at ~20 km depth while in the southern part the seismicity is located at a shallower depth, 10 km in average.

A schematic view of the main findings above reported is shown in Fig. 8a, where the relocated seismicity is superimposed on a geological section redrawn from Argnani *et al.* (2003). The geologic section derives from the interpretation of seismic reflection lines originally published with depths in time [TWT, Argnani *et al.* (2003)]. The conversion to the depth in kilometres has been performed using the references contained within the paper by Argnani *et al.* (2003) (depth of the Moho, extension to depth of the units). In Fig. 8b the tomographic results of Scafidi *et al.* (2009) are displayed as background of the cross-section.

The different seismic behaviours between the western and eastern sectors in the cross-sections can now be attributed to the difference between the western (Tyrrhenian) domain,

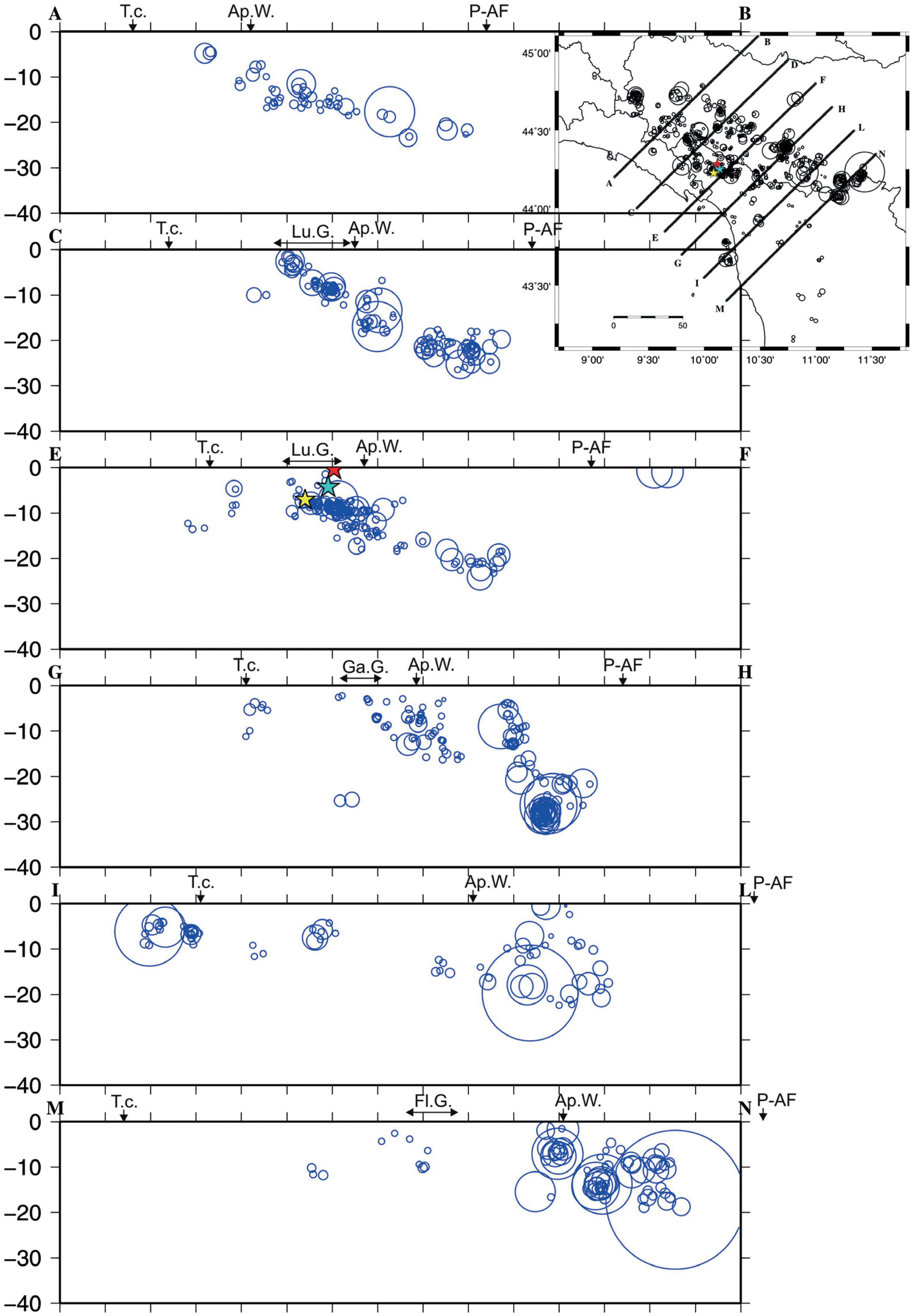

Fig. 6 - SW-NE oriented seismic cross-sections. Coloured stars show the historical earthquakes (yellow: 1995; light blue: 1920; red: 1837). T.c. = Tyrrhenian coast; Ap.W. = Apennine watershed; P-AF = Pede-Apennine thrust front; Lu.G. = Lunigiana graben; Ga.G. = Garfagnana graben; Fl.G. = Florence graben. The width of the cross-sections is 20 km.

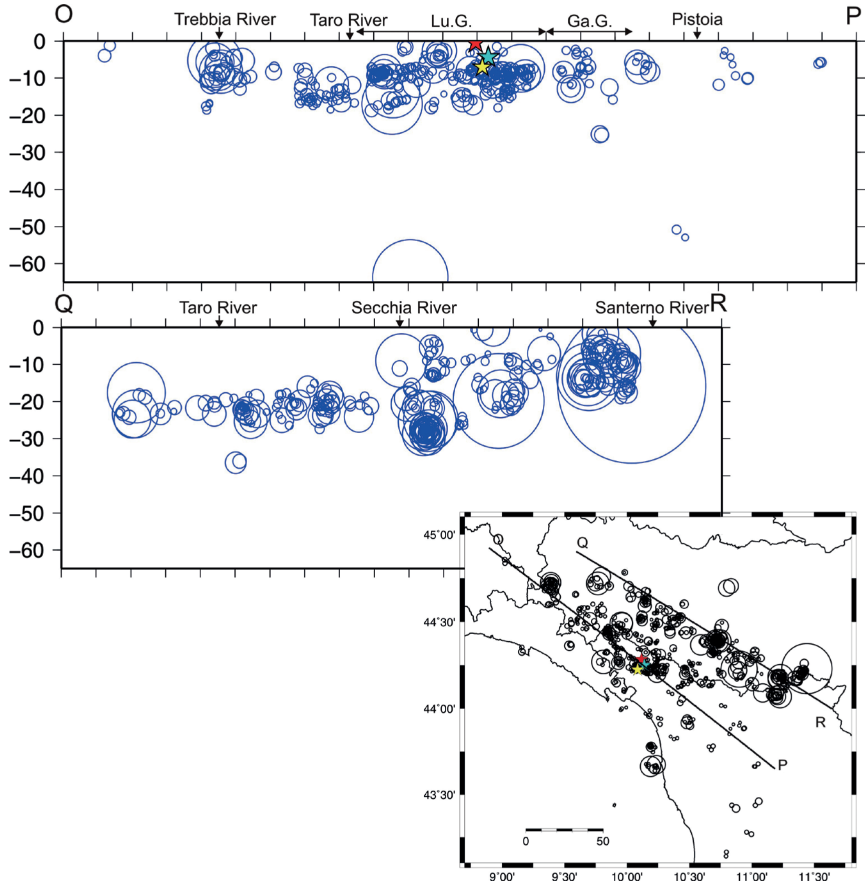

Fig. 7 - NW-SE oriented cross-sections. Coloured stars show the historical earthquakes (yellow: 1995; light blue: 1920; red: 1837). The O-P section crosses longitudinally the Lunigiana and Garfagnana grabens; the Q-R section is located between the Lunigiana and Garfagnana grabens and the front of the pede-Apennine thrust; Lu.G. = Lunigiana graben; Ga.G. = Garfagnana graben. The width of the cross-sections is 30 km

characterized by a thin crust, and the eastern (Adriatic) domain, characterized by a thick crust. In particular, the shallow seismicity of the Tyrrhenian sector seems to coincide with the top of the basement, corresponding to an E-dipping extensional detachment (Argnani *et al.*, 2003). The similarities between the top of the basement and the belt of seismicity, in terms of both geometry (E-dipping at ~30°) and lateral extent in cross section, strongly suggest this interpretation, though the seismicity locates slightly below the top of the basement in Figs 8a and 8b. This shift could be due to a combination of factors, such as i) intrinsic errors in the location procedure, which are somehow reduced by the applied algorithm; ii) errors in converting at depth the geo-seismic section; and iii) non-cylindrical geometry of the top of the basement in the NW-SE direction, coupled with the large width of the volume of seismicity projected on the section (10 km-wide from the section trace).

The observed E-deepening of the seismicity, clearly visible in all the Lunigiana area (sections A-B, C-D and E-F in Fig. 6), and its likely association to an extensional detachment are features similar to those found in the Umbria region of the central Apennines. There, geologic data and accurately-located background seismicity allowed some authors to define an E-dipping low-angle normal fault [Altotiberina fault: Boncio *et al.* (2000) and Chiaraluce *et al.* (2007)].

The deeper seismicity of the Adriatic sector locates within the deep compressional structures of the eastern Apennines, between the thrust emerging along the pede-Apennine front (P-AF in Fig. 1a) and the thrust of the Ferrara-Romagna folds (FFR in Fig. 1a).

## 5. Conclusions

About 1200 selected earthquakes occurred in the north-western Apennines have been relocated through the high precision location methodology HypoDD. Due to the complex history of the seismic network and the very restrictive criteria to choose events for the seismotectonic interpretation, only about 70% of the events reached the quality threshold of vertical and horizontal errors.

The obtained database of well-located earthquakes and its spatial distribution allowed us to confirm, with a significantly improved detail, a number of features previously proposed in the literature (Solarino *et al.*, 2002a, 2002b), in particular:

- in map view the earthquakes mostly locate into two NW-SE-trending zones of seismicity, west and east of the Apennine water divide, separated by an almost aseismic corridor; the interpretation of this feature needs a more complete analysis including geodetic, heat flow and presence of fluid data. However, it must be remarked that, as shown in Fig. 8, the aseismic sector is a complex area which corresponds to the transition between the European and the Adriatic crusts, the deep and shallow earthquakes as described in this article and the different kinematic models derived from the focal mechanisms. All these may suggest that the aseismic zone is a ductile area "sandwiched" between different domains, as proposed by rheological studies in other areas (Bodri, 1996).
- in the western zone the seismicity is systematically shallower (< 20 km) than the eastern zone (up to 20-30 km).

Most important, our analysis constrained for the first time three main geometric features that appear to be of particular interest for the seismotectonic interpretations of the Lunigiana-Garfagnana seismicity. In particular:

1) most of the seismicity of the western zone is located within the Lunigiana graben, north-NW of the Apuane Alps;
2) in cross-section, the hypocentres of the Lunigiana seismicity align along a narrow seismic zone that dips ~30° to the east. The hypocentres are very shallow in the western part, close to the western border of the Lunigiana graben, and deepens to about 20 km in the eastern part, beneath the Apennines. When compared to a seismic reflection profile (e.g., Argnani *et al.*, 2003), this alignment of seismicity appears to be parallel to the top of the basement, which in turn coincides with an extensional detachment, suggesting that this detachment is controlling the distribution of seismicity in the area;
3) the Lunigiana seismicity terminates southwards with a dense cluster of epicentres oriented nearly E-W, parallel to the northern boundary of the Apuane Alps; south of this cluster, a strong reduction of seismicity is observed and the locations are shifted to the eastern sector.

These findings might help in interpreting the seismotectonics of past earthquakes. In fact,

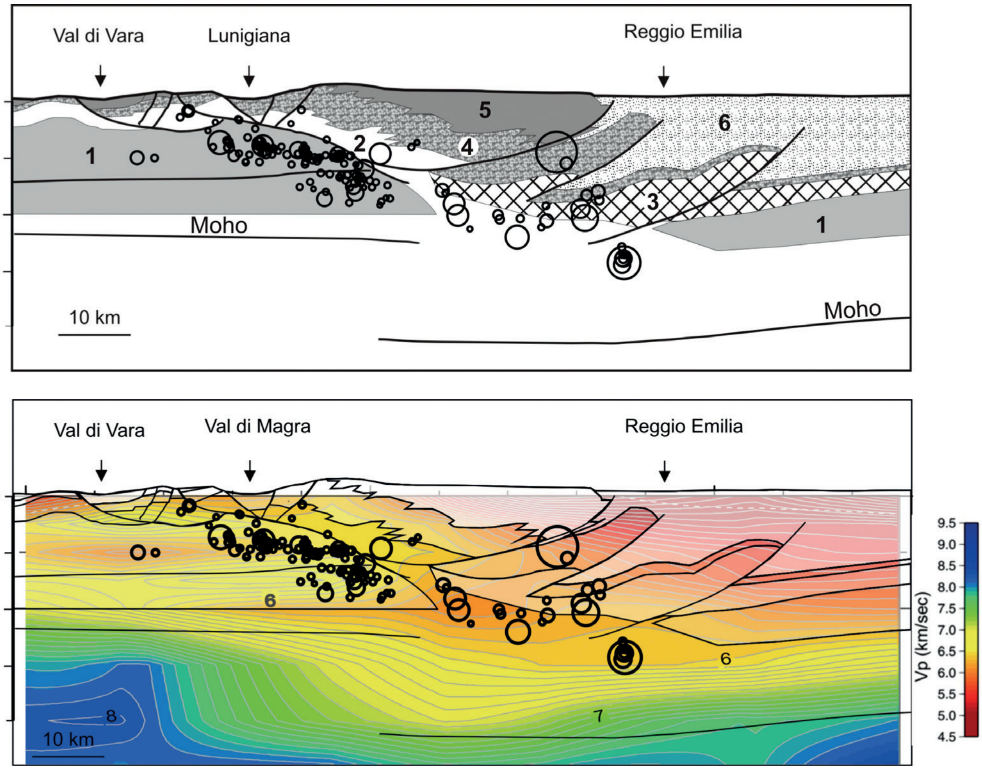

Fig. 8 - a) Relocated seismicity superimposed on a geological cross-section constrained by seismic reflection data (redrawn from Argnani *et al.*, 2003); location of section trace in Fig. 1; 1 = basement units; 2 = strongly deformed Mesozoic units; 3 = weakly deformed Mesozoic units; 4 = Oligocene-Miocene foredeep sediments; 5 = Ligurian units; 6 = Pliocene-Quaternary foredeep sediments. b) Section (a) superimposed on tomographic results (from Scafidi *et al.*, 2009).

though major earthquakes struck this region in 1481, 1837, 1920 and 1995, little is known about their focal depth and causative source. The 1837, 1920 and 1995 earthquakes are located close to the E-W-trending cluster of seismicity, at the southern boundary of the Lunigiana graben. A possible interpretation of the observed frame is that this E-W-trending cluster of seismicity is controlled by a zone of transfer faulting having normal-oblique - to - strike-slip kinematics. Normal-oblique right-lateral kinematics on nearly E-W-striking planes is indicated by slip vectors on faults cropping out near Equi Terme (Brozzetti *et al.*, 2007), while almost pure strike-slip right-lateral kinematics on an E-W-striking plane is suggested by the focal mechanism of the 1995 ($M_d$ 4.9) earthquake.

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