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ORIGINAL ARTICLE

Seismicity of Northwestern Italy during the last 30 years

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Abstract The aim of this work is to describe the seismicity of Northwestern Italy from the very detailed picture provided by 30 years of accurate instrumental recordings coming from the Regional Seismic Network of Northwestern Italy (RSNI—University of Genoa). In an attempt to provide, for the first time, a comprehensive view of the seismicity in the area, this study describes the main characteristics of the database collected by the RSNI network. The seismicity is spread almost over the entire area, but it is mainly concentrated in the Northern Apennines and in the western sector of the Alps. The seismicity of the area is superficial: It is almost confined to the first 20 km of depth. Only a few deeper events are located in a small area southwest of the city of Turin, down to a depth of 80 km, and below the Northern Apennines down to 60–70-km depth. The majority of the earthquakes in this sector of the Italian peninsula are of low magnitude; nevertheless, the areas where the highest magnitude earthquakes took place during the last three decades are the Northern Apennines and the lower Piedmont, on land, and the Ligurian Sea, offshore. They are indeed the areas where the most damaging historical earthquakes have occurred, giving emphasis, if necessary, to the importance of continuous seismic monitoring.

Keywords Seismicity · Northwestern Italy · Western Alps · Ligurian Sea · Northern Apennines

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1 Introduction

The northwestern part of the Italian peninsula, encompassing the western Alpine arc, the Ligurian Sea, the western Po Plain, and the Northern Apennines, has a very complex geodynamical framework (Fig. 1). Its recent geodynamic history started with the N-S to NNE-SSW convergence of the European and African plates which was followed by the continental collision over the Tertiary Period that led to the closure of the Alpine Tethys Ocean (Upper Cretaceous-Eocene). During the last phases of the collision, the Adria microplate, which detached from the African plate, rotated in a counterclockwise direction, resulting in the creation of a south-dipping continental subduction zone and the emplacement of the European lower crust under the Apulian micro-plate (Blundell et al. 1992). The Western Alps were created as a result of this geodynamic process. In the Oligocene, the counterclockwise rotation of the Sardinia-Corsica block led to the oceanization of the Ligurian-Balearic basin. The following counterclockwise rotational crustal shortening that led to the formation of the Northern Apennines (Oligocene-Miocene) left behind an extensional regime that caused the

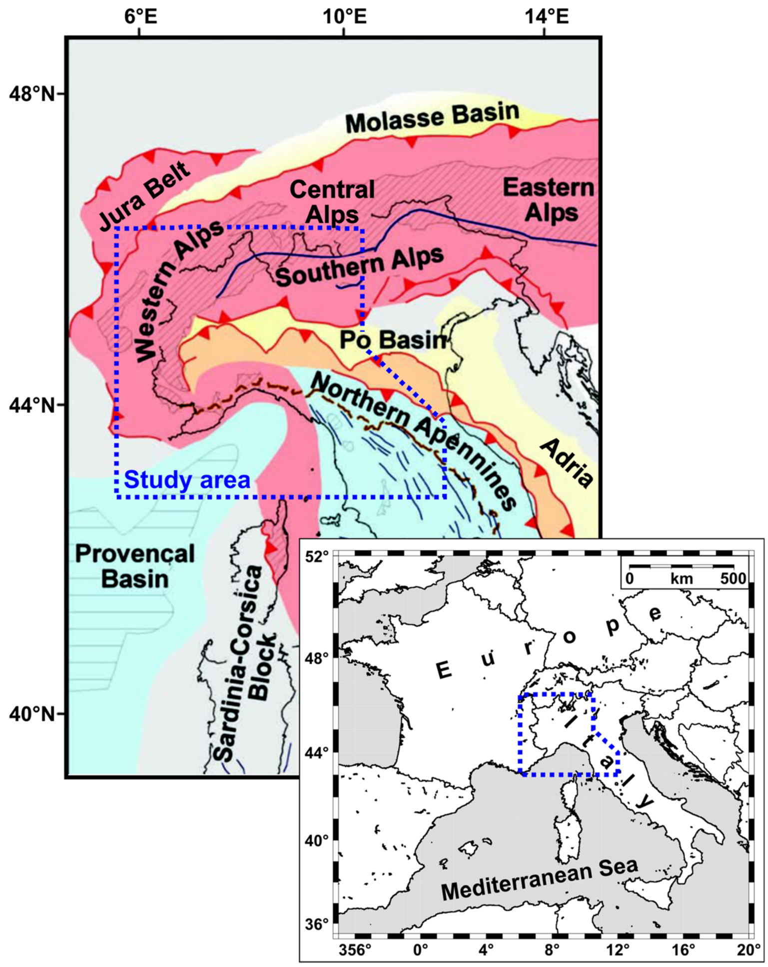


Fig. 1 Geographic position and simplified tectonic framework (from Scrocca et al. 2003) of Northwestern Italy

opening of the Tuscan graben system (Upper Miocene-Pliocene) (Carmignani and Kligfield 1990).

Northwestern Italy was shocked by strong earthquakes in the past. Focusing on the Ligurian Sea, the largest historical event occurred on February 23, 1887 with a moment magnitude M_w=7.0 (Rovida et al. 2011), causing severe damage and losses near Imperia (e.g., Ferrari 1991). This event was felt over a wide area, encompassing Northern Italy, Southern France, and Corsica. About 600 people were killed and more than 2,000 injured. This earthquake, as well as the majority of offshore seismicity, is attributable to the activity of the fault system that characterizes the foot of the continental slope (Augliera et al. 1994; Eva et al. 1999). Other significant earthquakes occurred in February 1818 (M_w=5.5), May 1831 (M_w=5.5), December 1854 (M_w=6.7), and July 1963 (M_w=6.0). Except for the 1831 earthquake, which may be associated with the Saorge-Taggia fault system (Giammarino et al. 1978; Spallarossa et al. 1997; Turino et al. 2009), the remaining events presumably occurred offshore, contributing significantly to the regional seismic hazard (Barani et al. 2007).

Concerning the Northern Apennines, it is worth mentioning the destructive September 7, 1920 Garfagnana earthquake (M_w=6.5). The ground shaking induced caused destructive damage throughout almost all the Lunigiana-Garfagnana (Northern Tuscany), in an area of around 160 km^2, and was felt up to the Cote D'Azur in Southern France, Aosta in Northwestern Italy, the Friuli region in the northeast, and south of Perugia in Central Italy. This event is attributed to the activity of the Garfagnana North fault (Basili et al. 2008), a low-angle normal fault extending parallel to the Apennines trend for approximately 18 km, which is responsible for the high rates of seismic moment (strain) release in the area of the Lunigiana-Garfagnana (Barani et al. 2010). Other strong events in the Northern Apennines occurred in May 1481 (Lunigiana earthquake, M_w=5.6), April 1837 (Alpi Apuane earthquake, M_w=5.8), and October 1914 (Garfagnana earthquake, M_w=5.8).

In Northwestern Alps, the strongest historical earthquakes are located in the Valais region (Western Swiss Alps), where the pronounced seismic activity is accompanied by a significant surface uplift (Ustaszewski and Pfiffner 2008). Here, the strongest earthquakes occurred on December 9, 1755 with M_w=6.1 (Gisler et al. 2004) and January 25, 1946 with M_w=6.0.

2 RSNI instrumental database

In an attempt to provide, for the first time, a comprehensive view of the seismicity in the area, this study describes the main characteristics of the seismic database collected by the Regional Seismic Network of Northwestern Italy (hereinafter RSNI, "GU" internationally coded, http://www.distav.unige.it/rsni), in the last 30 years. The current station distribution is shown in Fig. 2. This database contains seismic data accurately viewed and processed by expert seismologists and earthquake locations computed through the Hypoellipse (Lahr 1999) code using different 1D

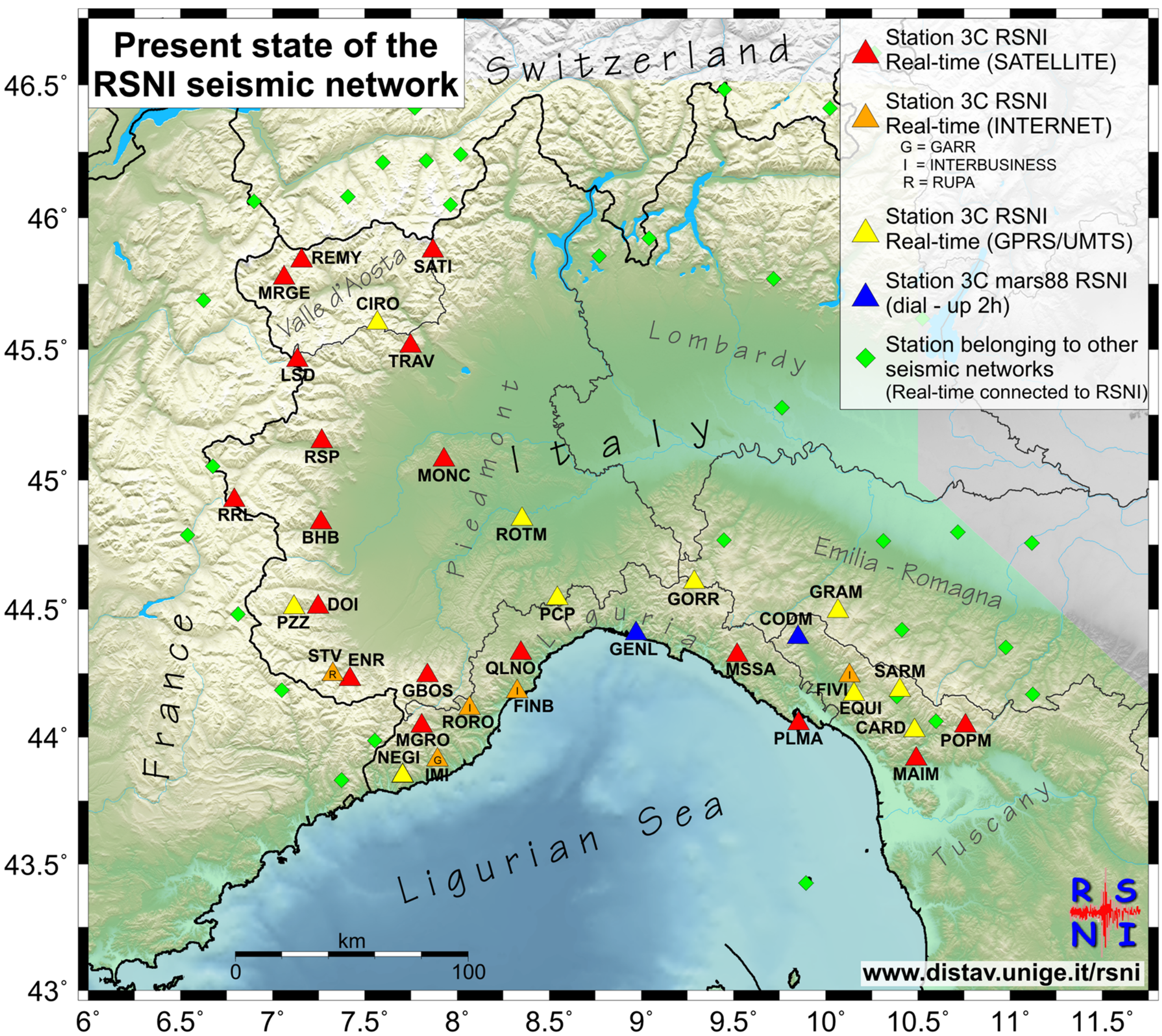


Fig. 2 The actual geometry of the RSNI seismic stations installed in Northwestern Italy belonging to the RSNI seismic network and other interconnected surrounding networks. The seismic stations are differentiated depending on the type of transmission system

velocity models which were calibrated for each station to take into account lateral heterogeneity and were derived from deep seismic profiles and tectonic constraints (Cattaneo et al. 1999; Spallarossa et al. 2001).

In the early 1980s, a duration magnitude (M_D) scale was calibrated for each station by using the magnitude reported in the Laboratoire de Detection et de Geophysique (LDG, Bruyeres-le-Chatel, France) network bulletin, with no distance correction (Cattaneo et al. 1981). Such duration magnitude has been adopted for more than 20 years of seismological observations in the Western Alps. Spallarossa et al. (2002) showed that the M_D scale overestimates magnitudes below M_L 1.5 and underestimates magnitudes greater than M_L 4, and as a consequence, Bindi et al. (2005) proposed two local magnitude scales based on Wood-Anderson maximum amplitude for Northwestern Italy for both three-component broadband or semi-broadband stations and vertical short-period seismometers. The use of these latter magnitude scales has allowed us to compile the homogeneous seismic database described in this paper including local magnitudes over the whole period.

From January 1982 to August 2013, the RSNI network has detected and stored 36,878 earthquakes in Northwestern Italy and the surrounding areas. Although most of the earthquakes in this sector of the Italian peninsula are of low magnitude, there were 5,580 events with a magnitude greater than M_L 2.5, and 115 earthquakes with an M_L greater than 4.0. The magnitude distribution for the whole period (Fig. 3a) seems to be centered around M_L 2.0 (left panel), whereas by only analyzing recent data (right panel), it turns out that the central value is around M_L 0.8, with a lot of very low magnitude events in the area. This discrepancy is strictly related to the recent evolution of the RSNI network that has led to a significant decrease in the magnitude detection threshold. This is also more evident looking at the magnitude distribution per day (Online Resource 1) where a great change in the recording sensibility is appreciable starting from November 2007. The completion of the renewal of the seismic network with the switch to a fully digital transmission and acquisition system has led to the significant enhancement (Pasta et al. 2011) that occurred at the end of 2007. The use of a new phase-picking procedure (Spallarossa et al.

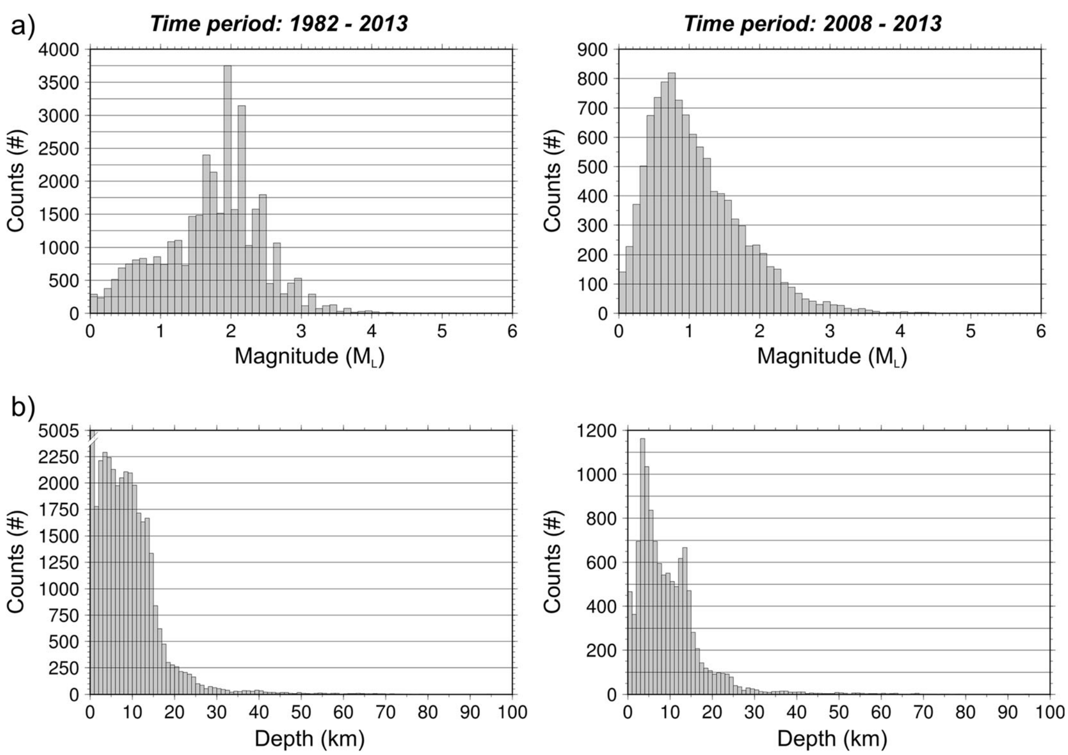


Fig. 3 Histograms showing the depth and magnitude distribution of the seismic events located through the RSNI for the period 1982–2013 (*left panels*) and for the last 6 years (*right panels*)

2014; Turino et al. 2010) has further lowered the automatic event detection threshold to M_L values close to zero starting from 2012, giving the possibility to detect and analyze a large number of small earthquakes that occur in Northwestern Italy.

For the reasons linked to the evolution of the seismic network mentioned above, the catalog has been subdivided into four homogeneous periods to estimate its completeness (Table 1). The magnitude of completeness (M_C) is determined as the point of maximum curvature of the frequency-magnitude curve (Wiemer and Wyss 2000; Mignan and Woessner 2012). In practice, this corresponds to the magnitude bin with the highest frequency of events in the non-cumulative Gutenberg and Richter distribution. From an initial M_C of 2.5 in the 1980s, and a constant M_C of 2.2 until 2007, the RSNI database has now a magnitude of completeness of 0.6.

3 Seismicity of Northwestern Italy

In order to have a detailed but reliable picture on the seismicity of the area, all the events with an M_L greater than 2.0 are mapped in Fig. 4, considering only events with location uncertainties in the horizontal (erh) and vertical (erz) plane less than 10 km.

In the last 30 years, there have been 22 damaging events with an M_L greater than 4.5 in the area monitored by the RSNI network. Their locations and characteristics are reported in Table 2, and their geographical positions are highlighted in blue in Fig. 4. The areas where the highest magnitude earthquakes took place during the last three decades are along the border between the Northern Apennines and the Po Plain (January 2012, M_L 5.7; December 2008, M_L 5.2), in Lunigiana-Garfagnana (June 2013, M_L 5.1; January 2013, M_L 4.8; October 1995, M_L 4.9), in the lower Piedmont (April 2003, M_L 5.1; August 2000, M_L 5.2), and in the Ligurian Sea (February 2001, M_L 4.6; April 1995, M_L 4.5). Furthermore, northwest of the Valle d'Aosta region, at the border between France and Switzerland, there have been some events of high magnitude (July 1996, M_L 4.9; December 1994, M_L 5.0). The seismicity distribution that comes out from these data is in agreement with the location of the main historical earthquakes for the area, described in the "Introduction".

Table 1 Magnitude of completeness (M_C) of the RSNI seismic database over time

Period	M_C
1982/01–1989/08	2.5
1989/09–1995/12	2.2
1996/01–2007/10	2.2
2007/11–2013/08	0.6

Seismicity is spread over almost the entire area, but it is mainly concentrated in the Northern Apennines and in the western sector of the Alps. A few aseismic zones are observed in the Po Plain and in some smaller regions, like the southwestern Piedmont and the area northeast of Genoa. Finally, a quasi-aseismic band is splitting the Northern Apennines into two distinct seismic areas.

One of the main features of the seismicity is the existence of two branches which depart from the southern sector of Western Alps at about 44.300° N latitude, firstly defined by Rothé (1941) and now sharply depicted. The two alignments create a corridor of less frequent seismicity and seem to reunite at the border with Switzerland. The recent addition of seismic stations in the Valle d'Aosta region is providing more hints to the shape of the northern end of these branches and on the seismicity of the region itself.

Between the Western Alps and Northern Apennines, there are other seismic sources spread all over the western part of the Ligurian coastline, onshore and offshore, while the eastern sector of this region is almost aseismic.

The hypocentral distribution of the seismicity can be analyzed in cross sections of Fig. 4, which cut the whole study area in a convenient way (Eva C., personal communication), and in the map of Online Resource 2. This map shows the focal depth of the seismicity, and it is calculated averaging the depth of the earthquakes located inside 500-m-wide boxes. Such a small grid has been chosen and manually checked to have only very few events for every box and therefore to avoid possible masking effects due to the presence of clusters of events or events with significant difference in depth in the same box. Also, the interpolation used to draw the map has a very light smoothing to present an image as close as possible to the actual situation. In a general overview of the hypocentral distribution, the seismicity of the area is superficial; it is almost confined in the first 20 km of depth, as also confirmed by the histogram in Fig. 3b. Furthermore, the larger earthquakes are mostly superficial and confined to this depth range, except for the January 2012, M_L 5.7, isolated event

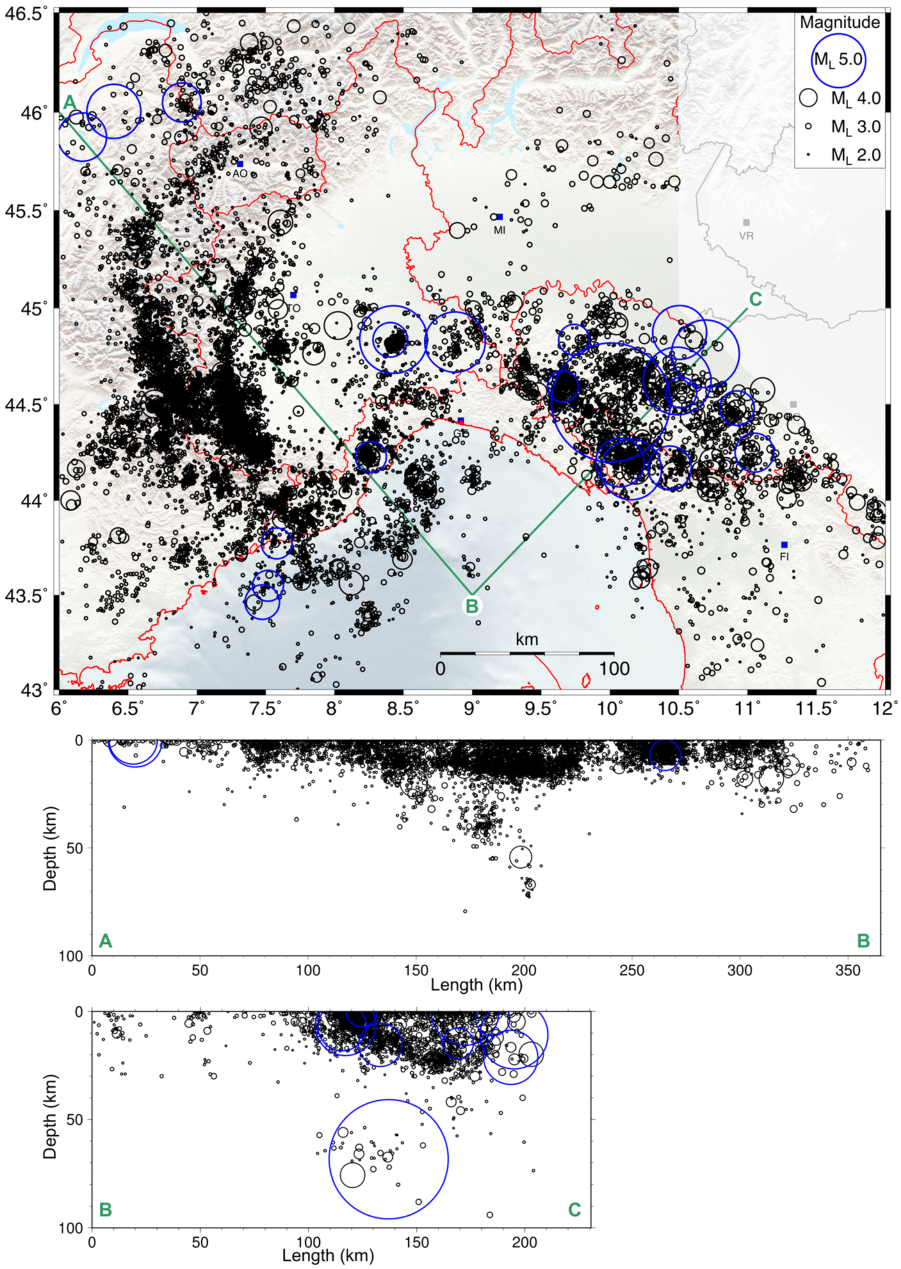


Fig. 4 Map and cross sections showing the distribution of earthquakes with $M_L \geq 2.0$ recorded in the last 30 years from the RSNI network. Only earthquakes with horizontal and vertical location errors less than 10 km are reported. Earthquakes with $M_L \geq 4.5$ are highlighted in *blue*. Cross sections are ±50 km wide

that occurred in the Northern Apennines at 68.3 km of depth.

As previously noted, Northwestern Italy presents very different areas from the seismic point of view, and for this reason, the seismicity will be analyzed in details splitting the main structural domain of the area (e.g., the Western Alps, Ligurian Sea, and Northern Apennines) in the following paragraphs. For each analyzed area, *b* values were also calculated by applying the maximum likelihood method proposed by Weichert (1980). They are summarized in Table 3 along with *a* values and the values of the cutoff magnitude, *M*c, below which data are incomplete (i.e., below which there is a falloff of the number of earthquakes toward lower magnitudes).

Table 2 List of the 22 events with an M_L greater than 4.5 that occurred in the last 30 years in Northwestern Italy

Time	Location (Lat-Lon)	Depth (km)	M_L	Area
1983 November 09 16:29	44.628–10.328	19.0	**5.0**	Appennino Parmense—Langhirano (PR)
1985 August 15 18:58	44.593–9.658	5.0	4.5	Appennino Parmense (PR)
1989 December 26 19:59	43.550–7.517	13.0	4.5	Ligurian Sea (France)
1993 July 17 10:35	44.227–8.263	7.0	4.5	Finale Ligure (SV)
1994 December 14 08:55	46.003–6.397	5.0	**5.0**	Alta Savoia (France)
1995 April 21 08:02	43.773–7.580	7.0	4.5	Ventimiglia (IM)
1995 October 10 06:54	44.198–10.073	7.0	4.9	Lunigiana (MC)
1996 July 15 00:13	45.874 –6.167	5.0	4.9	Alta Savoia (France)
1996 October 15 09:56	44.763–10.694	10.9	**5.2**	Reggio Emilia (RE)
1999 July 07 17:16	44.249–11.051	12.0	4.7	Appennino Bolognese (BO)
2000 August 21 17:14	44.837–8.428	5.0	**5.2**	Monferrato (AL)
2001 February 25 18:34	43.463–7.474	8.1	4.6	Ligurian Sea (France)
2001 July 18 22:47	44.836–8.405	5.0	4.6	Monferrato (AL)
2003 April 11 09:26	44.824–8.875	5.9	**5.1**	Lower Piedmont (AL)
2005 September 08 11:27	45.920–7.110	5.40	4.7	SW—Switzerland
2007 October 18 15.42	43.943–10.581	52.6	4.5	Borgo a Mozzano (LU)
2008 December 23 15:24	44.519–10.382	26.7	**5.2**	Appennino Reggiano (RE)
2008 December 23 21:58	44.527–10.355	23.7	4.8	Appennino Reggiano (RE)
2012 January 27 14:53	44.511–10.008	68.3	**5.7**	Appennino Parmense—Berceto (PR)
2012 October 03 14:41	44.836–9.740	19.6	4.5	Appennino Piacentino—Gropparello (PC)
2013 January 25 14:48	44.170–10.434	15.5	4.8	Garfagnana (LU)
2013 June 21 10:33	44.161–10.434	6.5	**5.1**	Lunigiana—Equi Terme (MC)

The eight earthquakes with an M_L greater than 5.0 are highlighted in bold

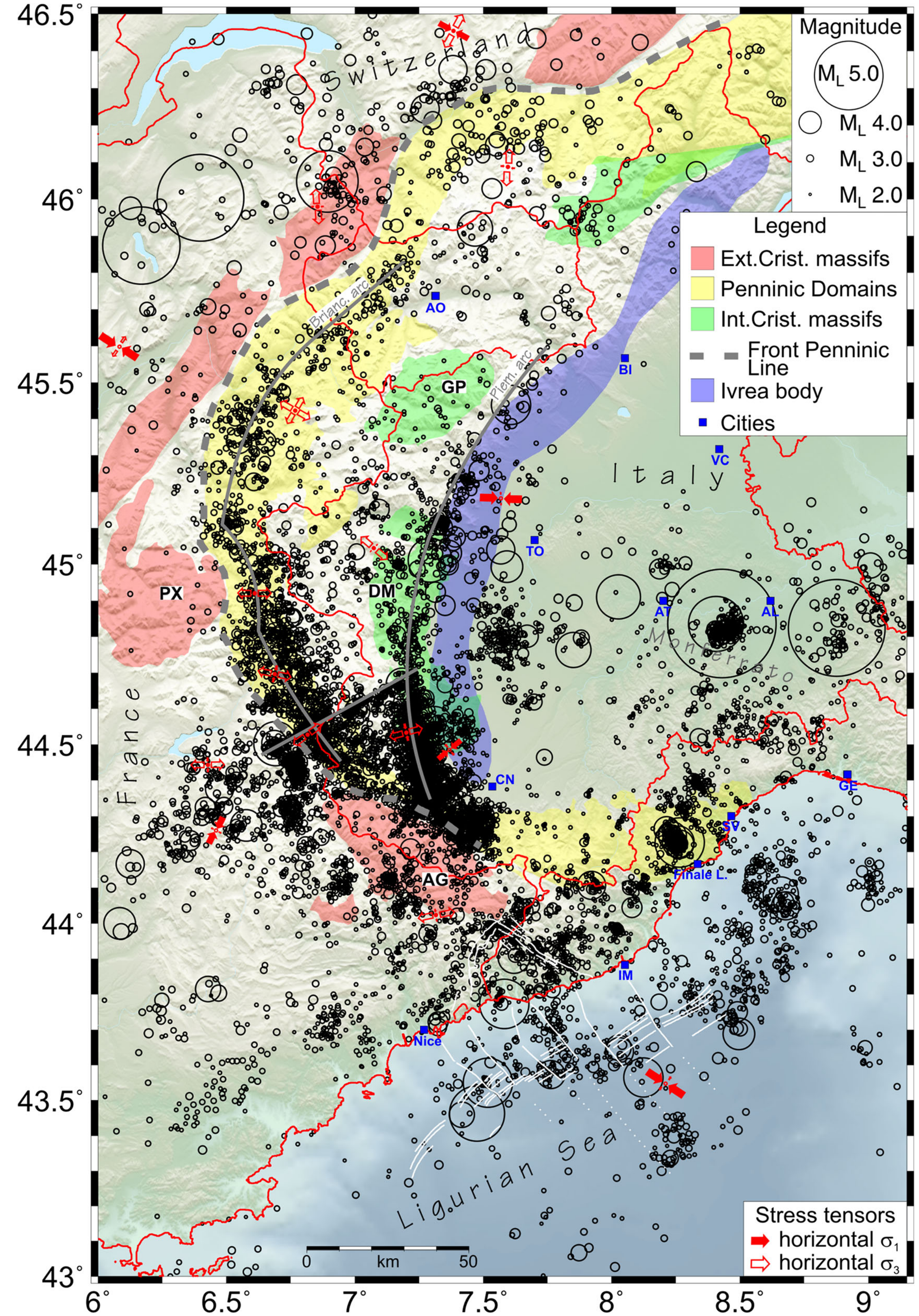
3.1 The Western Alps and Ligurian Sea

The Western Alps are the most seismically active area monitored by the RSNI network, characterized by frequent low-energy events (M_L<3.0). In Fig. 5, the seismicity is imposed over the main geological and geophysical features of this area.

Table 3 *b* values, *a* values, and values of the cutoff magnitude, *M*c, calculated for each of the areas analyzed in the text

Area	*b* value	*a* value	M_C
Western Alps (north)	1.21	4.11	2.0
Western Alps (south)	1.27	4.60	2.0
Northern Apennines (west)	0.90	3.59	2.0
Northern Apennines (east)	0.89	3.57	2.5
Western Liguria (onshore)	1.31	4.25	2.0
Western Liguria (offshore)	1.03	3.37	2.0
Monferrato	0.95	3.11	2.0

The seismicity is very dense and frequent just at the border N-NE of the Argentera (also called Mercantour) external crystalline massif (AG in Fig. 5). Two distinct thin arcs of seismicity depart from this area toward the north. The western one is the Brianconnaise arc (Rothé 1941) that follows the Penninic Front Line trend. Its seismicity is located almost within the first 12 km of depth. The eastern one is the Piedmont arc (Rothé 1941), which is interposed at the border between the Alps and the Po Plain and follows the western side of the high-velocity anomaly of the "Ivrea body" (Scafidi et al. 2006, 2009). Here, the seismicity is slightly deeper, between 8 and 20 km of depth. The volume comprised between the two arcs is characterized by widespread seismicity, except for the southern part, just north of Argentera where the seismicity is still diffuse up to a clear seismic lineation that perpendicularly links the two arcs (WSW-ENE-oriented gray line in Fig. 5). This lineation represents the border between an area with a higher seismicity rate southward and a lower one northward, as also pointed out by Table 3. The two areas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Front Penninic Line
Ivrea body
Cities
Stress tensors
horizontal σ1
horizontal σ3
Switzerland
Italy
France
Ligurian Sea
Monferrato
Brianc. arc
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◀ **Fig. 5** Seismicity in the Western Alps and Ligurian Sea superimposed on the main geological (modified from Schmid et al. 2004) and geophysical (modified from APAT 2005; Scafidi et al. 2006) features of the area. Labels for external crystalline massifs are as follows: PX—Pelvoux and AG—Argentera. Labels for internal crystalline massifs are as follows: Gran Paradiso (*GP*) and Dora Maira (*DM*). Faults in the Ligurian Sea and Western Liguria area (*white lines*) (Camprendon et al. 1977; Chaumillon 1992; Cosani 1997; Turino et al. 2009) and stress tensors (*red arrows*) (Delacou et al. 2004) are also plotted

(Western Alps North and South) have different earthquake productivity with the southern sector presenting both higher *a* and *b* values.

The emplacement of the Argentera crystalline massifs clearly influences the geometry of the seismicity with its quasi-aseismic behavior, in contrast with the nearby areas. It is, in fact, also bordered in its western part by seismicity that is here more clustered than widespread. Also, the Pelvoux external crystalline massif (PX in Fig. 5) influences the shape of the seismicity of the "Brianconnaise arc," which is curved eastward just in correspondence of this body. The internal crystalline massifs, like the Dora-Maira (DM in Fig. 5), instead do not seem to have any influence on the current distribution of seismicity.

The analysis of the first 220 km of the cross section AB of Fig. 4 points out that the seismicity of the Western Alps deepens eastward, following the curved geometry of the mountain chain, starting at very shallow depths in France and Switzerland and deepening down to 20 km near the Po Plain in Piedmont. This is also in agreement with the very shallow (0–7-km depth) seismicity at the northwestern border of the area between Switzerland and France, where in the last 30 years, three earthquakes took place with magnitudes greater than M_L 4.5, the only ones in the entire western Alpine arc (Fig. 4). There is then a small area south of the city of Turin where there are only few deeper events, down to 80-km depth, in contrast with the overall seismicity of this sector that is almost focused in the first 20 km of depth. This area is situated in the eastern flank of the "Ivrea body."

According to the seismic behavior, from a tectonic point of view, the Western Alps can grossly be divided into an internal and an external sector. The internal sector that follows the topographic crest line of the Alpine arc has an extensional regime with the major T-axes (maximum extension) almost perpendicular to the structural trend of the Western Alps, following a radial pattern (Fréchet 1978; Nicolas et al. 1990; Champagnac et al. 2004; Delacou et al. 2004), as pointed out from focal mechanism solutions and GPS data analysis (Calais et al. 2002; Nocquet and Calais 2003, 2004). The external sector which is located near the western Po Plain border has instead a compressive-transpressive regime with a counterclockwise rotation of the major P-axes (maximum compression) from north (ENE-WSW-oriented) to south (N-S-oriented) following the shape of the Alpine belt (Delacou et al. 2004).

Moving our attention toward the Liguria region and the Ligurian Sea, two distinct seismic districts can be distinguished (Fig. 5): one onshore and one offshore.

Inland, the seismicity is mostly assembled in clusters elongated perpendicularly to the coastline at a depth confined to the first 10 km. One of these clusters in the middle of the region, near Finale Ligure ("Finale L." in Fig. 5), consists of no less than eight seismic sequences in the last 30 years, as also better shown in Fig. 8 and Table 4. Another area with a high rate of seismicity is the western part of Liguria, at the border with France, where the seismicity is mainly associated to the Saorge-Taggia and to the Breil-Sospel-Monaco fault systems, which are both presumed to be strike-slip (Giammarino et al. 1978; Eva et al. 1999), and to other correlated seismic lineaments, as recently pointed out from a seismotectonic study on the area (Turino et al. 2009).

Offshore, at about 20 km from the coastline at the bottom of the continental slope, the other seismic district can be found. Here, the hypocenter is deeper than inland, down to a depth of 25 km (see the last sector of cross section AB in Fig. 4), and they follow the system of faults perpendicular and parallel to the coast shown by other studies in this area and reported in Fig. 5 (Chaumillon et al. 1994). The interpretation of seismic profiles, including the data recorded during the MALIGU (Chaumillon 1992) and GROSMARIN (Dessa et al. 2011) cruises, shows that the continental slope here is very steep, and it is characterized by pre-Pliocene step faults and shallow faults parallel to the coast that are intersected by a more recent fault system NW-SE oriented (Eva et al. 1999). Moving farther offshore, in the middle of the Ligurian basin, there is a sparse seismicity that reaches a depth of 30–35 km.

The onshore and offshore areas have slightly different earthquake productivity (Table 3), with the onshore sector presenting a higher rate of low-magnitude events (i.e., higher *a* and *b* values) with respect to the offshore area.

From a tectonic point of view, the Ligurian oceanic basin has a tensional origin, but recent seismological

Table 4 Main characteristics of the major seismic sequences occurring in the area in the last 30 years

Start time	Duration	Area	No of events	Average depth (km)	Max magnitude (M_L)	M1–M2
1982 October 18	8 days	Appennino Parmense (PR)	102	10.3	3.7	0.2
1987 May 28	4 days	Bellino—Valle Varaita (CN)	92	6.9	3.5	0.1
1993 March 15 *	6 days	Demonte—Valle Stura (CN)	80	8.9	4.3	2.1
1993 July 13	7 days	Finale Ligure (SV)	586	7.1	4.5	0.4
1993 December 17	9 days	Finale Ligure (SV)	89	5.6	4.0	0.1
1994 January 19	3 days	Dronero—Valle Maira (CN)	24	5.3	4.3	0.4
1994 November 13	1 day	Finale Ligure (SV)	75	8.6	2.4	0.0
1995 January 6	4 days	Finale Ligure (SV)	53	6.4	2.5	0.0
1995 April 21 *	10 days	Ventimiglia (IM)	79	9.3	4.5	1.6
1995 May 27	4 h	Finale Ligure (SV)	38	8.3	2.5	0.3
1995 October 10 *	21 days	Aulla—Lunigiana (MC)	116	6.0	4.9	1.9
1999 November 12	6 days	Bellino—Valle Varaita (CN)	50	9.2	2.8	0.1
2000 June 10	2 days	Garfagnana (MC)	74	12.8	1.8	0.1
2000 August 2	4 days	Finale Ligure (SV)	96	8.4	3.3	0.3
2000 August 20 *	7 days	Monferrato (AL)	108	12.3	5.2	1.7
2003 March 28	13 days	Demonte—Valle Stura (CN)	68	11.8	3.1	0.3
2004 May 14 *	11 days	Condove—Val di Susa (TO)	57	9.4	3.9	0.7
2006 April 1	10 days	Pontremoli—Lunigiana (MC)	22	7.6	3.8	0.4
2006 April 2	2 days	Fivizzano—Lunigiana (MC)	20	6.3	2.3	0.0
2008 March 1	5 days	Firenzuola—Apennines (FI)	91	8.1	4.2	0.1
2008 July 6	8 h	Finale Ligure (SV)	26	4.5	2.8	0.0
2008 October 24 *	4 days	Demonte—Valle Stura (CN)	51	10.6	4.1	1.2
2008 December 23 *	3 days	Appennino Reggiano (RE)	85	16.7	5.2	0.7
2010 August 5	14 h	Finale Ligure (SV)	46	6.1	1.5	0.1
2010 October 13	1 months	Sampeyre—Valle Varaita (CN)	550	12.2	3.2	0.2
2011 September 08	11 days	Appennino Parmense (PR)	133	13.6	3.6	0.3
2011 October 2	30 days	Santo Stefano d' Aveto (GE)	44	9.7	4.0	0.3
2012 October 3 *	17 days	Sampeyre (CN)	119	12.4	3.9	0.8
2013 January 25 *	3 months	Garfagnana (San Pellegrino) (LU)	471	13.9	4.8	1.6
2013 April 14	3 days	Val di Taro (PR)	31	12.3	2.3	0.1
2013 June 21 *	2 months	Lunigiana (Equi Terme) (MC)	2113	4.4	5.1	0.7

See text for details

data depict a present-day compression that might be responsible for the actual seismicity of the northern margin of the Ligurian Sea (Béthoux et al. 1992). Indeed, several focal mechanisms indicate the reactivation in compression of this part of the basin, probably due to the collision between the African and European plates in an N-S direction (Béthoux et al. 1992; Larroque et al. 2008). More specifically, major recent earthquakes in this area show compressive focal mechanisms with NW-SE principal horizontal stress vectors. Hence, Béthoux et al. (1992) suggest that the Ligurian Sea is currently closing and compression has been reactivating due to the lateral expulsion of the Southwestern Alps along the Apulian indenter. This reactivation process may be responsible for the high rates of deformation ($\approx 4.0 \times 10^{-8}$ years^{-1}) observed by Barani et al. (2010). Chaumillon et al. (1994) instead propose that this area is subject to a superposition of two strain regimes, a tensional one near the surface and a deeper compressional one.

Another noteworthy seismic area is the "Monferrato" region situated between Liguria and the Po Plain (Fig. 5). This area represents a transition zone between the Alps and Apennines, and it is characterized by low seismic activity, mainly concentrated at the border between the Apennines and the Po Plain, and by three of the largest earthquakes recorded in the last 30 years in Northern Italy (Table 2), which occurred in 2000, 2001, and 2003. The hypocenters are generally confined to the first 20-km depth, except for a few events which occurred during the 2000 "Monferrato" sequence (Massa et al. 2006) that reached a depth of 50 km. Earthquake sources are here supposed to be associated with the main pre-Burdigalian tectonic structures of the Tertiary Piedmont Basin and related to the "Monferrato" region subsidence (Piana et al. 2002; Massa et al. 2006). This area is characterized by the lowest *a* value in Northwestern Italy and by a *b* value very close to the ones of the Apenninic regions. The low seismic activity of this area is also confirmed by historical seismicity that counts only three seismic episodes with M_W around 5.0 in the catalog starting from the year 1000 (Rovida et al. 2011).

Of note is the presence of a completely aseismic small area trapped between the seismicity of the Western Alps, Western Liguria, and the "Monferrato" region, located northeast of Cuneo (CN in Fig. 5). This is the region where the European, Adriatic, and Tyrrhenian Moho collide (Spada et al. 2013), and it is not far from the supposed rotation pole of the Adria plate with respect to the European one, especially considering a composite rotation model for the Western Alps (Collombet et al. 2002). The aseismic behavior is also confirmed considering the whole RSNI database with no magnitude selection. This area, at the southern rim of the Western Alps, could be remarkable from the geodynamical point of view and could deserve future studies.

3.2 The Northern Apennines

The Northern Apennines are another seismically active area where several damaging earthquakes have occurred in the past. In Fig. 6 the seismicity recorded by the RSNI network in the last 30 years is superimposed onto the main seismogenic sources of the area as reported in the DISS 3.1 (DISS Working Group 2010): From northwest to southeast, they are the "Pontremoli" (1 in Fig. 6), "Aulla" (2), "Garfagnana North" (3), "Garfagnana South" (4), "Mugello West" (5), and "Mugello East" (6) fault systems. Stress regime and directions of the maximum horizontal compressional stress axis (S_{Hmax}) (Heidbach et al. 2008), also reported in Fig. 6, show a prevalent extensional regime in the Tyrrhenian part and a transpressive-compressive regime in the outer part of the Apenninic chain (Pierdominici and Heidbach 2012). More detailed information on the geology and tectonics of this area can be found, for example, in Di Naccio et al. 2013 and Bonini et al. 2014.

Looking at the distribution of the epicenters (Fig. 6), the seismicity is mainly concentrated in two separated sectors that follow the NW-SE orientation of the Apenninic chain. The first is situated east of the Liguria region border and comprises the Lunigiana and Garfagnana basins, in Northern Tuscany. This area is characterized by the presence of the back arc extensional basins of the peri-Tyrrhenian region dominated by extension since the upper Miocene (Ferretti et al. 2002). The Lunigiana and Garfagnana basins are two NW-SE-oriented asymmetric grabens bordered by NE-dipping and SW-dipping normal faults (Argnani et al. 2003).

Seismicity is generally spread all over this sector even if, NW of the border between Liguria and Tuscany and in between the Aulla and the Garfagnana North fault systems, it is characterized by the presence of more clustered events showing an anti-Apenninic (SW-NE) trend. A recent seismic sequence took place in June 2013 between the Lunigiana and the Garfagnana basins, activating a fault system with anti-Apenninic direction with a huge number of seismic events and a main shock of M_L 5.1. In these areas, also, a significant earthquake of M_L 4.9 occurred in 1995, and the main historical earthquakes took place. South of this sector, the seismicity becomes less frequent, and its distribution allows us to highlight the almost aseismic behavior of the core complex of the Apuane Alps. Another seismically active area is situated east of the junction between the Garfagnana North and Garfagnana South fault systems. Here, in January 2013, a significant seismic sequence after a main shock of M_L 4.8 took place, while no recent seismicity is present in the area of the Garfagnana South fault systems.

Looking at the depth distribution (cross section BC of Fig. 4 and Online Resource 2), the seismicity of this sector is almost entirely focused in the first 30-km depth, with the higher magnitude earthquakes (M_L>4.0) located in the shallower part of the crust. In more detail, the earthquakes deepen (from 0 to 30 km) eastward with a dip of almost 30–40°. A few deeper events are located

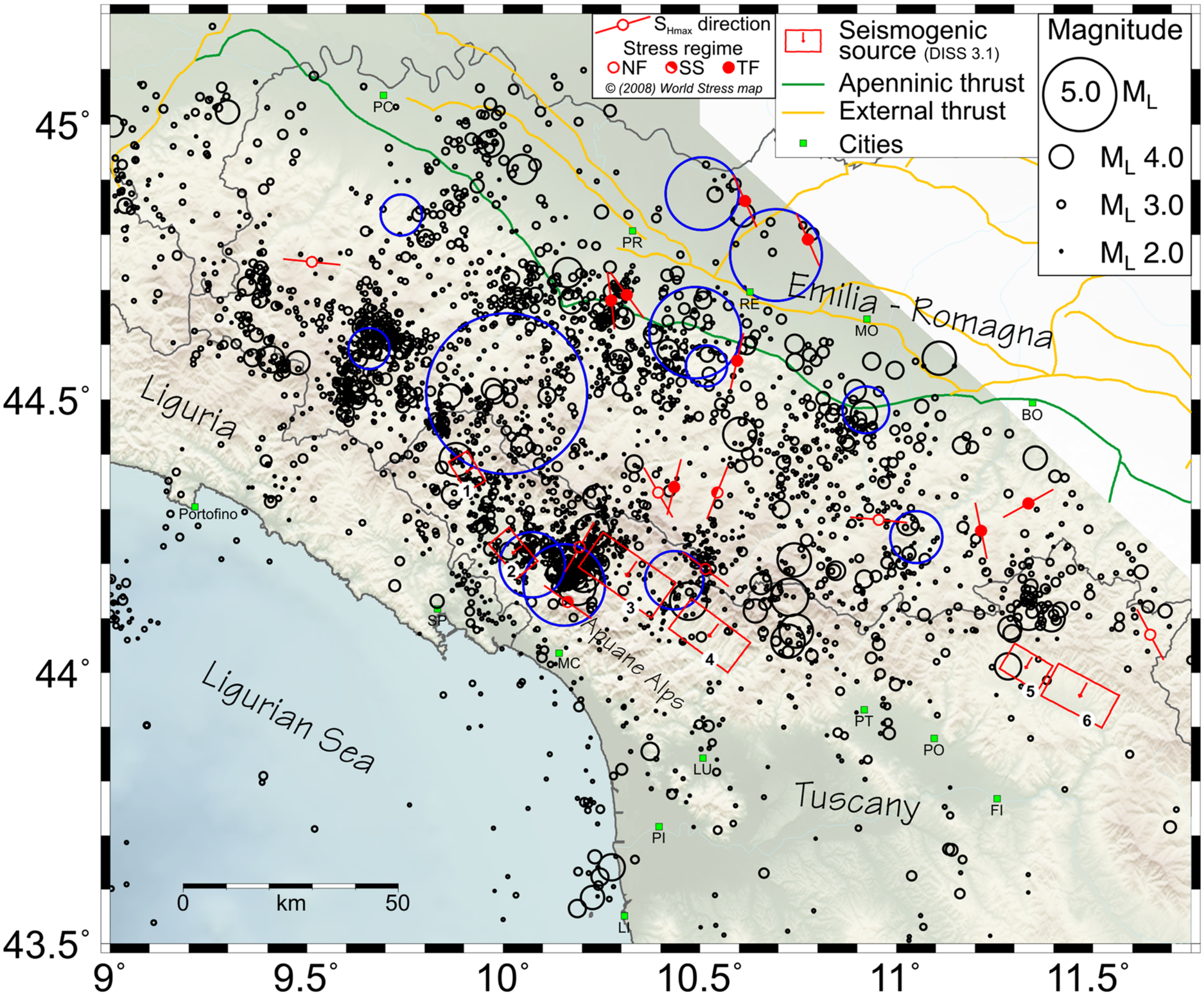

Fig. 6 Seismicity in the Northern Apennines superimposed on the main seismogenic sources (DISS 3.1, DISS Working Group 2010) and geological features (modified from Bigi et al. 1990) of the area. Stress regime and directions of the maximum horizontal compressional stress axis (S_{Hmax}) (Heidbach et al. 2008) are also plotted. Stress regime is as follows: normal faulting (*NF*), strike-slip faulting (*SS*), thrust faulting (*TF*)

between 50 and 80-km depth, and of note, almost no seismicity between the superficial and the deeper layers (e.g., 30 km<earthquake depth<50 km) is present. Only two isolated deeper events with medium-high magnitudes (one with M_L 4.3 and one with M_L 5.7) are located near the "Pontremoli" fault system, with hypocenters between 68 and 75 km of depth. The January 2012, M_L 5.7, isolated event is particular not only because of its focal depth but also mainly because, despite being the strongest of the whole Northwestern Italy in the considered period, it had no foreshocks and it was only followed by four aftershocks of M_L 2.8, 3.5, 2.1, and 2.3. Also, the other isolated M_L 4.3 event, which occurred slightly southwestern of the previous one at similar depth, shows the same behavior with no foreshocks and aftershocks at all. Even if the present dataset is here scarce, we can believe that this is a characteristic of the deeper seismicity of this Apenninic area. This could be related to the thermal (warmer) and rheological state of this area, which makes it a high-stress drop and low-seismic-efficiency area.

The second sector is situated eastward of the Apenninic watershed, near the border with the Po Plain, and it is separated by a quasi-aseismic narrow area from the previous sector. From a tectonic point of view, this is a belt-foredeep region along the Adriatic margin characterized by crustal shortening (Reutter 1981; Royden et al. 1987). The seismicity is deeper than in the previous sector, being concentrated in the first 50-km depth, and, in the Emilia-Romagna region, it follows a prevalent anti-Apenninic trend (NE-SW direction) from the foot of the Apenninic chain to the Po Plain.

In terms of earthquake depth distribution, in contrast to the previous sector, the seismicity deepens toward the west with a quasi-vertical dip. In this sector, 6 of the 22 damaging earthquakes with an M_L greater than 4.5 which occurred in the last 30 years in Northwestern Italy took place, including two events with M_L 5.2 near Reggio Emilia (RE in Fig. 6) (see Table 2).

The comparison of *a* and *b* values for the northeastern and northwestern sectors of the Apennines (Table 3) indicates that the two areas present a similar proportion of small and large earthquakes.

4 Seismic sequences and swarms

To characterize the seismic rates of the area, a plot of the daily seismicity of the last 30 years is reported in Fig. 7, together with the cumulative seismic moment (M_0) to also show the evolution of the release of earthquake energy with time, which reaches a value of 2.95E+18 in the last 30 years. The seismicity is generally uniformly distributed in time with an average rate of about three earthquakes per day, even if several swarms and seismic sequences (with an average number of events spanning from 20 to 300 earthquakes per day) are also present. Of note, the increasing sensitivity of the RSNI seismic network, starting from 2008, has allowed us to better recognize sequences characterized by many low-magnitude events (e.g., M_L<2.0) and with an average duration of a few days.

The most significant seismic sequences and swarms are mapped in Fig. 8 and listed in Table 4, which reports their geographical locations and main features (e.g., number of events, time duration, and magnitude range). They have been recognized by an accurate manual inspection of the seismic catalog based, at first, on the occurrence time to trigger the presence of a possible sequence (or swarm) and then on the belonging of that earthquakes to the same fault system within 15 km. Only sequences (or swarms) exceeding a minimum number of 20 earthquakes that occurred within 15 km in about 24 h

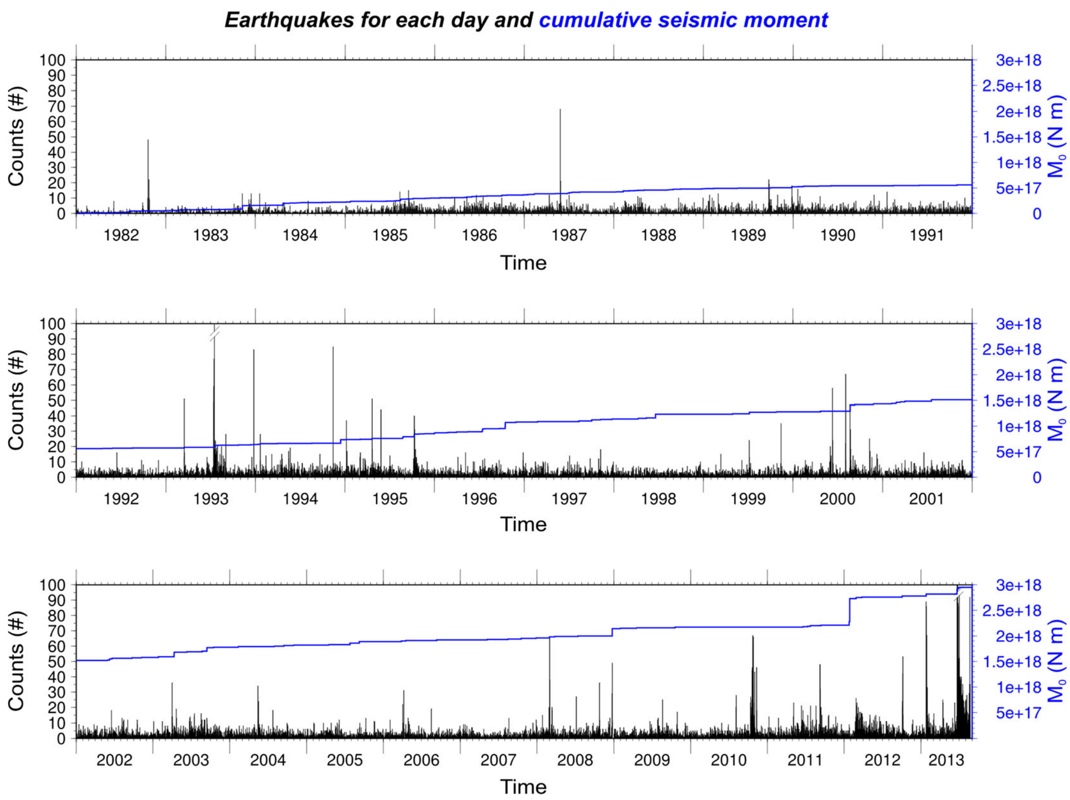

Fig. 7 Histograms showing the number of events per day as recorded by the RSNI network in the last 30 years with diagrams of the cumulative seismic moment (M_0)

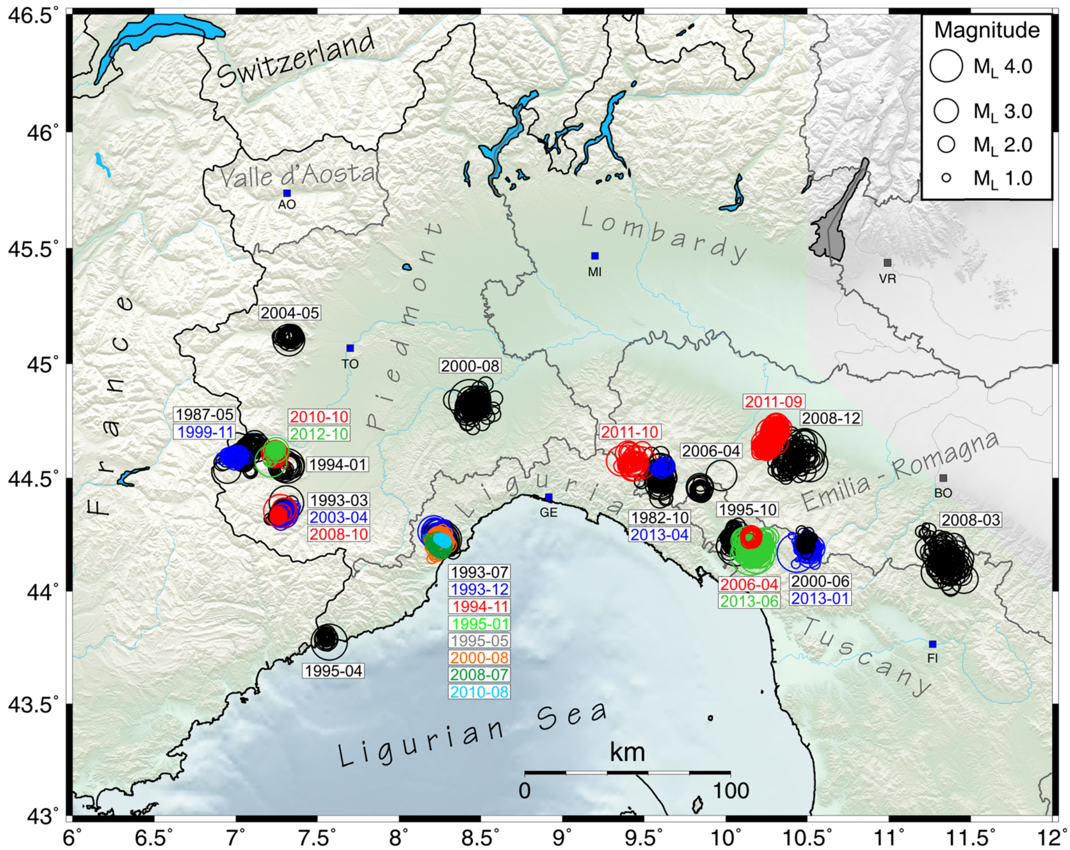

Fig. 8 Map showing the locations and the times of occurrence of the most significant (more than 20 events in 24 hours) seismic sequences that occurred in Northwestern Italy in the last 30 years

have been considered in this paper since they represent all the most significant ones of Northwestern Italy. However, it should be noted that many other smaller clusters of events are frequently found in the whole area.

Ten seismic sequences are marked with an asterisk in Table 4 to distinguish them from the other 21 seismic swarms. This distinction is mainly based on the presence of a first main shock followed by a series of minor aftershocks (a typical MS-AS sequence) for the sequences, while in a swarm, the difference between the magnitudes of earthquakes is not so evident, and the higher magnitude event is both preceded by a series of foreshocks and followed by aftershocks. In the last column of Table 4, the difference between the magnitude of the main shock (M1) and the largest aftershock (or foreshock) (M2) is reported. The distinction between sequences and swarms is here also evident. Sequences show values in a range between 0.7 and 2.1, while swarms have lower values between 0.0 and 0.4.

All sequences are characterized by the lack of foreshocks except the December 2008 "Appennino Reggiano" main shock of M_L 5.2 preceded by only one M_L 3.1 foreshock, and the August 2000 "Monferrato" M_L 5.2 main shock, that will be discussed further on, preceded by 13 foreshocks in the days before, with the largest one of M_L 3.0.

The area with the highest rate of seismic swarms is near Finale Ligure (Western Liguria), where eight swarms occurred in the last 30 years, including the one which occurred in July 1993 with almost 580 earthquakes in 7 days. As pointed out also by Cattaneo et al. (1999), the seismicity is here associated with a fault system perpendicular to the coastline, active in the first 10 km of depth and characterized by an almost vertical dip.

Another area affected by seismic swarms and sequences is the northwestern part of the province of Cuneo (in the southwestern Piedmont), where different seismic episodes occurred in the Alpine Stura, Maira, and Varaita valleys, near the western flank of the Ivrea body. The most recent seismic swarms shook the central Varaita valley in October–November 2010, when about

550 earthquakes occurred in 1 month, and in October 2012 with a main event with M_L 3.9 followed by 118 aftershocks. This sector of the Western Alps is located in the Dora Maira crystalline massif which corresponds to the northern Tethyan margin (part of the stretched European continental crust), exhumed during the collision of the Eurasia and Africa plates. The 2010 earthquake swarm took place at a depth comprised between 5 and 20 km, following a focal plane SE-oriented and dipping almost vertically, with the activation of two distinct interacting fractures having different seismic productivity (Barani et al. 2014).

South of the previous area, the "Ventimiglia" seismic sequence occurred in April 1995 with a main shock of M_L 4.5, and, north of the previous area, the "Condove" sequence occurred in May 2004 with a main shock of M_L 3.9. Both represent an individual episode in their respective region.

The Northern Apennines are also characterized by the occurrence of both seismic swarms and sequences (Ferretti et al. 2005), including some of the highest magnitude events of the last 30 years, such as the October 1995 "Lunigiana" earthquake of M_L 4.9, the December 2008 "Appennino Reggiano" event of M_L 5.2, the January 2013 "Garfagnana" event of M_L 4.8, and the most recent June 2013 "Lunigiana" event of M_L 5.1. The seismic episodes are located in the western sector of the Apenninic chain, mainly in the Lunigiana-Garfagnana area, in the eastern sector of the chain at the foothill and near the Mugello basin. They took place in the first 20 km of depth, except for the two that occurred in the area between the Apenninic chain and the Po Plain (December 2008 and September 2011) that reached a maximum depth of 30 km. Of note, the chronologically last sequence that occurred in Lunigiana has been, by far, the largest one for a number of events, counting more than 2,000 earthquakes in 2 months. This sequence shocked an area comprised of the provinces of Lucca and Massa Carrara, between the Lunigiana and the Garfagnana basins, activating a fault system with anti-Apenninic direction. The M_L 5.2 main shock occurred near the municipalities of Minucciano (Lucca) and Casola in Lunigiana (Massa Carrara), and it has been followed by other energetic aftershocks, with local magnitude up to 4.4.

Finally, one particular seismic sequence occurred in the "Monferrato" area (Southeastern Piedmont) in August 2000 (Massa et al. 2006). This sequence is characterized by a main earthquake of M_L 5.2 and includes both foreshocks and aftershocks. It is worth noting that an event of M_L 4.8 occurred 1 year later in the same place. In this area, the seismicity is located at depths down to around 20 km. Focal mechanism solutions, relative to the main events of the above-mentioned sequence, indicate a prevailing strike-slip component with a nodal plane SW-NE-oriented (as also indicated by the distribution of all events of the sequence) (Massa et al. 2006).

5 Conclusions

Northwestern Italy and the surrounding areas have been monitored by the RSNI seismic network since the 1960s. The development of the network, characterized by continuous growth in terms of the number and quality of seismic stations, starting from 1982 and especially since 2008, allows us to have a comprehensive and complete view of the seismic patterns of this complex and seismically active area.

In this work, the earthquake locations of the last 30 years have been selected as a function of quality (i.e., location errors) to depict, for the first time, a complete and reliable image of the seismicity of Northwestern Italy. The seismicity of the area is characterized by an average rate of about three earthquakes per day and by the occurrence of 115 seismic events above the damage threshold (22 of which with an M_L greater than 4.5).

Four different seismic areas may be distinguished and separately analyzed. In the Western Alps, two different seismic arcs, departing from the N-NE border of the Argentera crystalline massif, are clearly shown. It should be noted that the external crystalline massifs of the Argentera and Pelvoux are almost aseismic and strongly influence the distribution of the current seismicity. South of the Western Alps, the Western Liguria and the Ligurian Sea are characterized by two distinct seismic districts, one onshore where the seismicity is located down to a depth of 10 km, and it is mostly associated with fault systems perpendicular to the coastline, and one offshore where the earthquakes are deeper (down to 25-km depth) and belong to fault systems that are both perpendicular and parallel to the coast, located at about 20 km off the coast.

Moving eastward, there is the "Monferrato" region, recently shocked by a sequence characterized by a main event of M_L 5.2 and including both foreshocks and aftershocks distributed along a vertical structure SW-NE-oriented and located down to a depth of 20 km.

Trapped between these three seismic active regions, there is an interesting aseismic small area, at the southern rim of the Western Alps, around which three different types of Mohos collide and which is not far from the rotation pole of the Adria plate with respect to the European one.

The fourth area coincides with the Northern Apennines where the seismicity is concentrated in two separated sectors that follow the NW-SE orientation of the Apennines, separated by a quasi-aseismic narrow area just east of the Apenninic watershed. In the western sector, the seismicity is diffuse, except several clustered events located around the Garfagnana North fault system and shows a SW-NE trend, and is almost entirely confined to the first 30 km of depth. In the eastern sector, the earthquakes deepen toward the west with a quasi-vertical dip down to a depth of 50 km and follow a prevalent anti-Apenninic trend (NE-SW direction).

The depth distribution of the earthquakes recorded in the last 30 years shows that the area is characterized by superficial seismicity (earthquakes almost entirely confined to the first 30 km), even if a few deep events are located at a depth of 80 km in a small area southwest of the city of Turin and in the Northern Apennines near the "Pontremoli" fault system. In the latter area, at 68 km of depth, the January 2012, M_L 5.7, earthquake took place that is the highest magnitude event of the last years and was only followed by four aftershocks. In the same area and depth, also, another smaller event (M_L 4.3) lacks aftershocks at all. This could be an interesting characteristic of the deeper seismicity of this Apenninic area, deserving further study.

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