Recognition of periAdriatic Seismic Zones Most Prone to Next Major Earthquakes: Insights from a Deterministic Approach

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1 Introduction

The distribution of historical earthquakes indicates that a large portion of the Italian territory could be hit by strong earthquakes (e.g., Guidoboni et al. 2007). Since a large part of the building patrimony in Italy was realized without taking into account adequate antiseismic criteria (e.g., Di Pasquale et al. 2005; Crowley et al. 2009), it would be economically very difficult in the near future to achieve a significant mitigation of seismic risk in such a large zone. This objective could more easily be obtained if reliable information was available about the zones most prone

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S. D'Amico (ed.), *Earthquakes and Their Impact on Society*,
Springer Natural Hazards, DOI 10.1007/978-3-319-21753-6_2

to next strong earthquakes, where the limited resources now available could be concentrated.

An attempt at obtaining such kind of information could be made by taking into account the possible connections between the spatio-temporal distribution of major shocks and the progressive development of tectonic processes in the central Mediterranean region, which are mainly related to the complex short-term kinematics of the Adriatic plate. It is known that each strong shock triggers a perturbation of the strain field that propagates in the surrounding zones (post-seismic relaxation, e.g., Pollitz et al. 2006; Ryder et al. 2007; Ergintav et al. 2009; Ozawa et al. 2011). When the effects of such perturbation reaches other seismic zones they may modify the probability of fault activation or even cause an earthquake when the fault involved is close to seismic failure. The possibility that this phenomenon induces seismicity has been pointed out in a number of papers (e.g., Anderson 1975; Rydelek and Sacks 1990; Pollitz et al. 1998, 2004, 2012; Mikumo et al. 2002; Freed 2005; Freed et al. 2007; Brodsky 2009; Lay et al. 2009; Durand et al. 2010; Luo and Liu 2010; Viti et al. 2012, 2013), which show that the time and place of occurrence of a number of major shocks are compatible with the expected effects of post-seismic relaxation induced by triggering events. In particular, this phenomenon has been recognized for some Italian zones (Southern Apennines and Calabria) whose seismic activity seems to be significantly influenced by major seismic crises in Hellenic and Dinaric zones respectively (Viti et al. 2003; Mantovani et al. 2008, 2010, 2012).

The fact that past seismic activity may affect the spatio-temporal distribution of next shocks in the tectonic context here considered is instead supported by the time pattern of major earthquakes that occurred at the main periAdriatic zones since 1400 A.D. In the next section, we describe the evidence that may support the plausibility of the proposed approach and we discuss on how it may provide insights into the location of next strong earthquakes in the Italian peninsula.

2 Interaction Between Southern Apennine and Southern Dinaric Seismic Sources

The possibility that major earthquakes in the first zone may influence the probability of major shocks in the second zone was first suggested by the fact that the strong earthquake (magnitude M = 7.0) of April 1979 in the Montenegro area of the southern Dinarides was followed on November 1980 by a major event (M = 6.9) in the Irpinia zone of the southern Apennines (Fig. 1). This initial hypothesis has then been reinforced by the knowledge about the seismotectonic setting of the study area (Fig. 1) and the results obtained by the quantification of the post-seismic relaxation triggered by the 1979 Montenegro event, as synthetically described in the following.

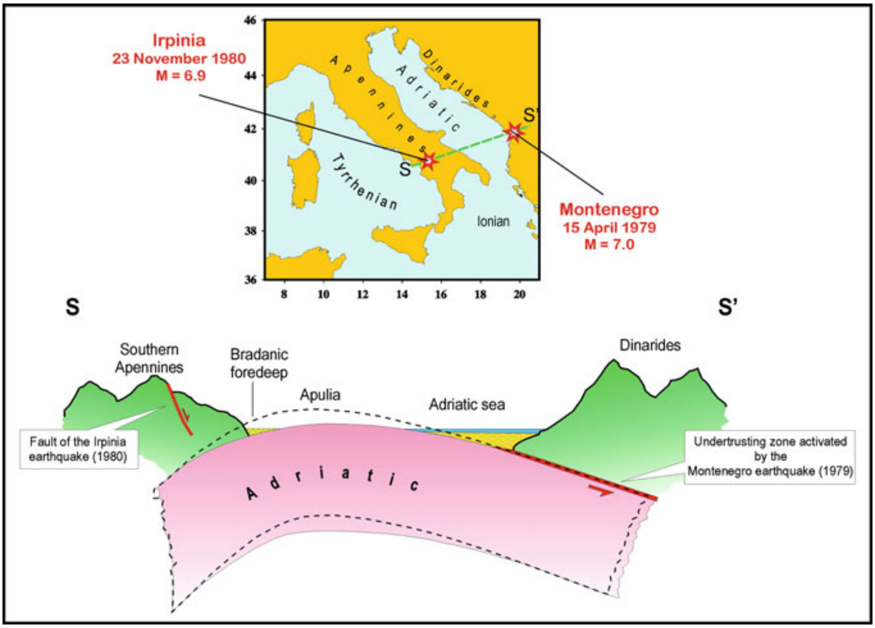


Fig. 1 Structural sketch, through a transversal section in the Southern Adriatic, which points out the vertical flexure of the Adriatic lithosphere overthrusted by the Dinaric belt, on one side, and by the Apennine belt on the other side (e.g., Moretti and Royden 1988; De Alteriis 1995). The vertical scale is exaggerated in order to make more evident the possible effect of a seismic slip (*red arrow*) between the Adriatic lithosphere and the Dinaric belt. The *dashed line* indicates the presumed profile of the Adriatic lithosphere before the Montenegro seismic slip. The epicentres of the 1979 (M = 7.0) Montenegro and 1980 (M = 6.9) Irpinia earthquakes and the trace of the section (green line) are shown in the map

The occurrence of seismic slip at a thrust fault beneath the Southern Dinarides, such as the one that developed with the 1979 Montenegro event (estimated to be 1–2 m, e.g. Benetatos and Kiratzi 2006), implies a roughly NE ward motion of the adjacent part of the Adria plate, which causes a reduction of the vertical flexure in the southern Adriatic domain. As sketched in Fig. 1, such process is expected to induce extensional strain in the Southern Apennines, which may favor the activation of the belt parallel normal faults recognized in that zone (e.g., Ascione et al. 2007).

This hypothesis is confirmed by the results of numerical modelling of the strain perturbation that was presumably induced in the Irpinia zone by the 1979 Montenegro event (Viti et al. 2003; Mantovani et al. 2010, 2012). In particular, by the fact that the strain rate induced by the Montenegro earthquake is expected to reach its maximum amplitude in the Southern Apennines about 1–2 years after the triggering event, i.e. a delay fairly consistent with the time interval that elapsed between the April 1979 Montenegro and November 1980 Irpinia shocks. The possible relationship between stress/strain rate increase and triggering of seismic activity has been pointed out in several works (e.g., Pollitz et al. 1998; Toda et al. 2002; Viti et al. 2003, 2012, 2013).

The possibility that the interaction between Southern Dinaric and Southern Apennine seismic sources is not an isolated phenomenon is suggested by the comparison of the series of major shocks that have occurred in such zones in the last two centuries (Fig. 2). From the list given in this figure, it is possible to note that in the period considered all the shocks with M ≥ 6.0 in the Southern Apennines have been preceded within few years (less than 5) by one or more earthquakes with M ≥ 6 in the Southern Dinarides. Since the probability that such a regular correspondence merely occurs by chance is very small (Mantovani et al. 2010, 2012), it is plausible to suppose that the observed interrelation results from a tectonic connection between the two zones.

The above correspondence does not change significantly if weaker shocks (M ≥ 5.5) are considered, since only one of the 15 Southern Apennine events was not preceded by equivalent earthquakes in the Southern Dinarides. This evidence may imply that a fault in the first zone can hardly activate without the contribution of post-seismic perturbation triggered by one or more major shocks in the other zone.

The fact that this significant time correlation can be recognized for the most recent, complete and reliable part of the seismic catalogue gives good reasons to hope that this phenomenon may provide a tool for recognizing the periods when the probability of strong shocks in Southern Apennines may undergo a significant increase. In this view, the fact that no earthquakes have occurred in the Southern Dinarides since 1996 would imply that at present the probability of major shocks in

Southern Apennines (M ≥ 5.5)	Southern Dinarides (M > 5.5)
1998 (5.6)	**1996 (6.0)**
1990 (5.8, 5.5)	1988 (5.7), 1982 (5.7)
1980 (6.9)	**1979 (7.0,** 5.7, **6.4)**
1962 (6.1, 5.7)	**1962 (6.2), 1959** (5.6, **6.2,** 5.9), 1958 (5.6)
	1935 (5.6), 1934 (5.6)
1930 (6.6)	**1927 (6.0),** 1926 (5.8, 5.8),1922 (5.6), 1921 (5.6), 1920 (5.6, 5.6)
1910 (5.7)	**1907 (6.2,** 5.7), **1906 (6.4), 1905 (6.0, 6.6)**
	1896 (6.2, 5.9), **1895 (6.2),**1894 (5.9)
1885 (5.5)	**1876** (5.6, **6.3)**
	1870 (6.5), 1869 (6.2, 6.0, 5.6)
1857 (7.0)	**1855 (6.8, 6.6),** 1853 (5.7)
1853 (5.6), **1851 (6.4)**	**1852 (6.2), 1851 (6.0, 6.6, 6.2, 6.3),** 1850 (5.6), **1848 (6.4), 1843 (6.2,** 5.6)
1836 (6.0)	**1833 (6.5),** 1830 (5.6)
1831 (5.5)	**1827 (6.5)**
1826 (5.8)	1823 (5.7)

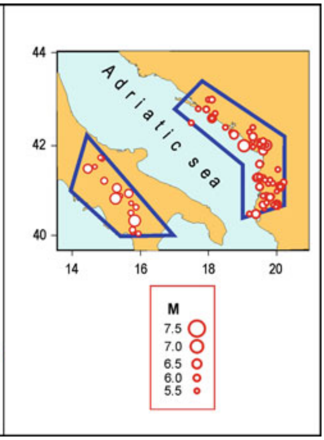


Fig. 2 Geometry of the zones implied in the presumed interrelation between Southern Dinaric and Southern Apennine seismic sources and list of the major seismic events occurred after 1810 (the shocks with M ≥ 6.0 are in *bold*). Data sources as in Appendix

the Southern Apennines is relatively low. A more detailed description of the seismic correlation cited above and a discussion about its possible uncertainties are reported in previous papers (Viti et al. 2003; Mantovani et al. 2010, 2012).

3 Interaction Between Calabrian and Hellenic Seismic Sources

Another significant correlation has been recognized between the major earthquakes of Calabria and those of the Hellenides sector lying between the Ionian islands and Albania (Fig. 3). The hypothesis that a strong seismic activation of the Hellenic thrust zone may increase the probability of major earthquakes in Calabria is consistent with the structural/tectonic setting sketched in Fig. 3. Indeed, such scheme suggests that a significant seismic slip at the Hellenic thrust zone is expected to produce a reduction of the upward vertical flexure of the Adriatic lithosphere, which may help the overthrusting of the Calabrian wedge, that is the process which is

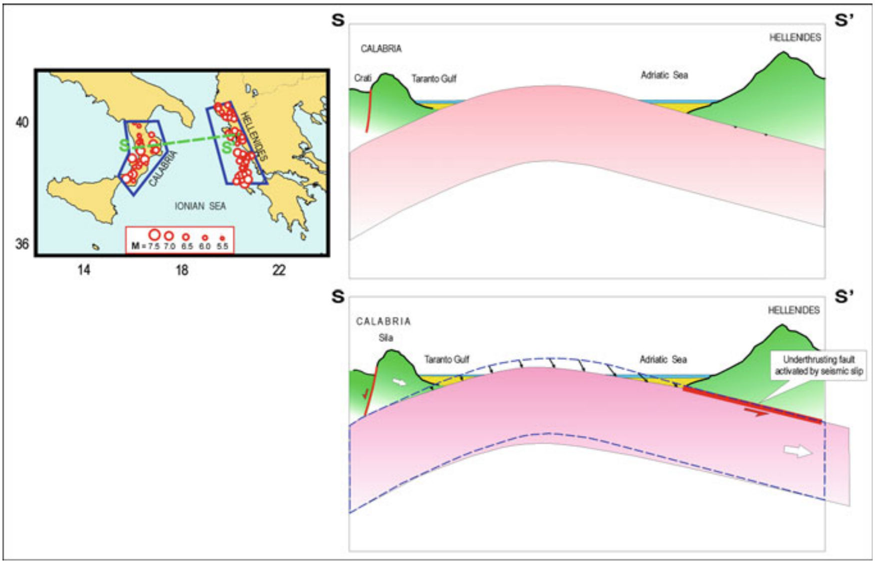


Fig. 3 The map shows the geometry of the two presumably interrelated Calabrian and Hellenic seismic zones, the trace of the section and the epicenters of the earthquakes occurred in the two zones since 1600 A.D. (*red circles*). The events considered are listed in Table 1. The *top section* shows a schematic reconstruction of the structural setting in the southern Adriatic area from Calabria to the Northern Hellenides. The *bottom section* illustrates a tentative reconstruction (*vertically exaggerated*) of the reduction of vertical flexure of the Adriatic plate (*dashed line*), which may occur in response to a strong decoupling earthquake at the Hellenic thrust zone. This effect may favour the outward escape of the Calabrian wedge towards the Ionian domain, presumably accompanied by seismic activation of its main fault systems

accommodated by the seismic activation of normal and strike-slip faults in Calabria (Mantovani et al. 2008, 2009, 2012).

The above interpretation and its implications on the interaction of the Calabrian and Hellenic seismic sources is consistent with the quantification of the effects of post-seismic relaxation induced by strong earthquakes in the Hellenides (Mantovani et al. 2008, 2012), which indicates that such phenomenon may have influenced the Calabrian shocks that occurred some years after the Hellenic triggering events.

The possibility that the above phenomenon has a systematic character is supported by the comparison of the seismic histories of the two zones involved (Table 1), which points out that all Calabrian shocks with $M \geq 6.0$ have been preceded, within 10 years, by at least one event with $M \geq 6.5$ in the Hellenides. If lower magnitudes ($M \geq 5.5$) are considered, the correspondence remains fairly significant, since only 2 (out of 26) Calabrian events have not been preceded by equivalent shocks in the Hellenides. The above evidence supports the hypothesis that a major Calabrian earthquake can hardly occur without being preceded by significant seismic activity in the Hellenic zone (Mantovani et al. 2012).

Concerning the opposite aspect of the presumed interrelation, one can note that only 12, out of 20, Hellenic seismic crises were followed by a Calabrian earthquake with $M \geq 6.0$. This indicates that the role of the Hellenic events as precursors of Calabrian shocks may be affected by uncertainty. In particular, it is worth noting that since 1948 no Hellenic events with $M \geq 6.5$ have been followed by an event in Calabria. This drastic increase of false alarms coincides with the latest period (since 1947) during which no earthquakes with $M \geq 5.5$ have occurred in Calabria (Table 1). Such long quiescence (66 years) is rather anomalous with respect to the previous behavior, in particular with the fact that from 1626 to 1947 the average inter-event time between $M \geq 5.5$ shocks was of 12 years and in any case it was never longer than 41 years.

In order to find a possible explanation of such long quiescence and of the fact that since the middle of the 20th century the correspondence between Hellenic and Calabrian earthquakes has undergone a considerable worsening, we advance the hypothesis that such anomalous behavior is an effect of a very rare major tectonic event that has drastically changed the strain and stress fields in the above zones. It concerns the large westward displacement that the Anatolian-Aegean-Balkan system has undergone in response to the series of very strong earthquakes that since 1939 activated the entire North Anatolian fault system (NAF) (e.g., Barka 1996). While activations of the easternmost (Erzincan zone) and westernmost (Marmara zone) sectors of the NAF have occurred other times in the past centuries (e.g., Ambraseys and Jackson 1998), the rare event was the fact that the post-1939 crisis involved an activation of the NAF central sector, that had been almost silent for several centuries. This event favored the migration of the whole Anatolian wedge, which noticeably strengthened the E-W compressional regime in the Aegean region (squeezed between Anatolia and Adriatic-Africa blocks). Considering the minimum work principle, it is reasonable to suppose that the fast shortening required by such dynamics was mainly accommodated by the outward extrusion of the Aegean zones (Peloponnesus and central Aegean) which face the Ionian oceanic domain. The extrusion of the northern Hellenides (facing the Adriatic continental domain) would

Table 1 List of major Calabrian and Hellenic events, with M ≥ 5.5 and M ≥ 6.0 respectively, occurred since 1600 A.D. in the zones depicted in Fig. 3

Calabria (M ≥ 5.5)	Hellenides (M ≥ 6.0)
	2003(6.2)
	1983(6.7, 6.0)
	1953(6.2, 7.0, 6.6)
	1948(6.5, 6.5)
1947(5.7)	
1928(5.8)	1920(6.0), 1915(6.1, 6.3, 6.0)
1913(5.7), 1908(7.1), 1907 (5.9), 1905(7.0)	1912(6.1), 1897(6.6), 1895(6.2, 6.2,6.5, 6.2)
1894(6.1)	1893(6.6)
1887(5.5)	1885(6.0)
	1872(6.0)
1870(6.1)	1869(6.7, 6.0), 1867(7.2), 1866(6.4, 6.3, 6.6), 1865 (6.3) 1862(6.2. 6.4). 1860(6.4)
	1859(6.0), 1858(6.4, 6.2, 6.0)
1854(6.2)	1851(6.8)
1836(6.2)	1833(6.5)
1835(5.8), 1832(6.6)	1825(6.7), 1823(6.3)
	1820(6.6), 1815(6.3)
1791(6.0)	1786(6.5), 1783(6.6, 6.5)
1783(7.0, 6.6, 7.0)	1773(6.5)
	1772(6.1), 1769(6.8)
1767(6.0)	1767(6.7), 1766(6.6), 1759(6.3)
	1745(6.0)
1744(5.7), 1743(5.7)	1743(6.9), 1741(6.3), 1736(6.0)
	1732(6.6), 1723(6.3), 1722(6.3), 1714(6.3), 1709(6.2)
1708(5.5)	1704(6.4), 1701(6.6)
1693(5.7)	
	1674(6.3), 1666(6.2)
1659(6.6)	1658(6.7), 1650(6.2)
	1638(6.3)
1638(7.0, 6.9)	1636(72), 1630(6.5)
1626(6.0)	1625(6.5)
	1613(6.3), 1612(6.3)
	1601(6.3)

Data sources as in Appendix

instead have involved much higher resistance. This hypothesis may explain why since about 1945 most seismic activity in such area has affected the Aegean structures lying south of the Cephalonia fault system and of the North Aegean trough, while a much lower seismic activity has occurred in the Northern Hellenides (Fig. 4).

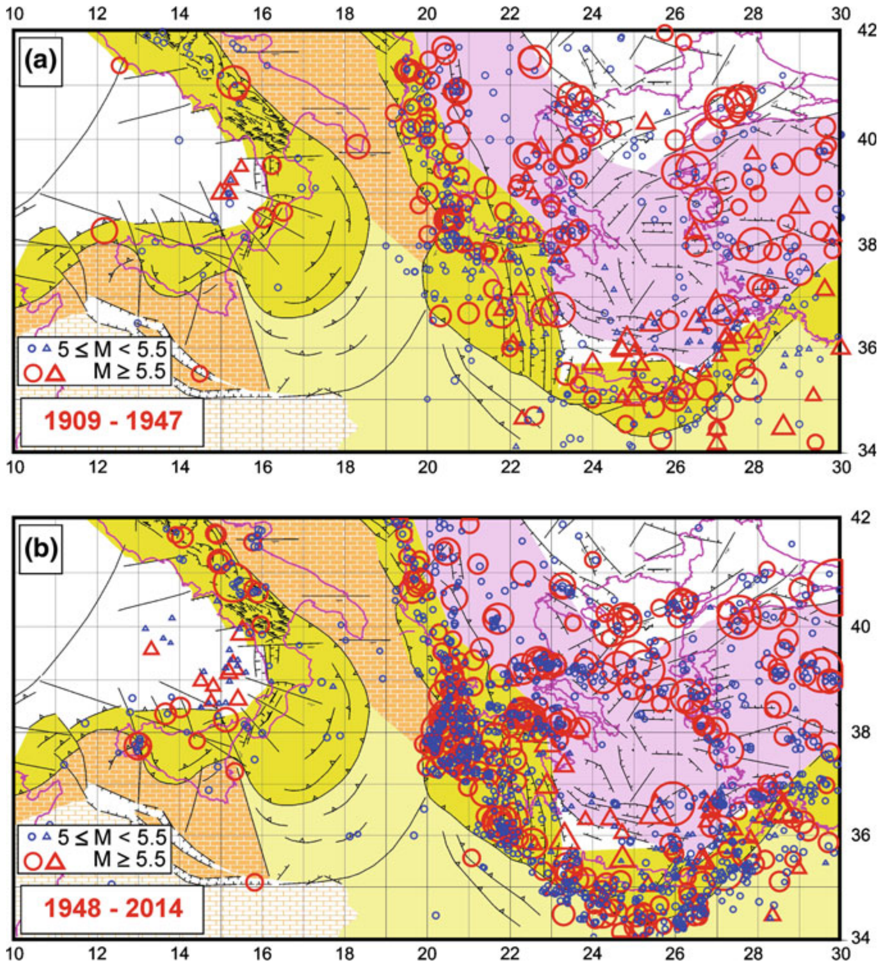


Fig. 4 Distribution of major earthquakes (M > 5) in the Anatolian-Aegean-Balkan system in two time intervals (**a** 1909–1947 and **b** 1948–2013) which respectively preceded and followed the arrival in the Aegean area of the effects of the large westward jump of Anatolia (see text for comments). *Circles* and *triangles* indicate earthquake epicentres with depth ≤60 and >60 km respectively. Seismic data have been taken from: Ergin et al. (1967), Rothé (1971), Ben-Menahem (1979), Makropoulos and Burton (1981), Iannaccone et al. (1985), Comninakis and Papazachos (1986), Ambraseys and Finkel (1987), Anderson and Jackson (1987), Eva et al. (1988), Jackson and McKenzie (1988), Godey et al. (2006), ISC Catalogue: http://www.isc.ac.uk/iscbulletin/. Other references as in Appendix

Since the activation of the Northern Hellenides thrust zone is supposed to be a necessary triggering of Calabrian seismicity (Fig. 3 and Table 1), the above evidence (Fig. 4) can explain why no major earthquakes have occurred in Calabria since 1947 (Table 1). The same interpretation helps understanding why in the period 1850–1908 (Table 1), that was characterized by very high seismic activity in the Northern Hellenides, very strong earthquakes have instead occurred in Calabria.

The evidence and arguments described above suggest that at present the probability of strong earthquakes in Calabria is relatively low and it is expected to remain so until seismic activity in the Northern Hellenides again undergo a significant increase.

This case may offer an interesting example of the different predictions of seismic hazard in Calabria that can be derived by a probabilistic evaluation, based on the local seismic history, and by the above deterministic approach based on the knowledge of the seismotectonic context. Assuming that seismicity is a Poissonian process (e.g., Stucchi et al. 2011), the probabilistic approach would predict a relatively high probability of earthquakes at present, due to the fact that the time elapsed since the last strong shock (about 70 years) is considerably longer than the average return period in that zone (about 12 years). The deterministic approach, instead, predicts a relatively low probability, considering that the present strain rate field in the zone involved (induced by a rare and presumably long living tectonic event) may prevent the development of the process (the outward escape of the Calabrian wedge) that is expected to favour the activation of main fault systems in Calabria.

4 Migration of Seismicity Along the periAdriatic Zones

The present knowledge about the geodynamics and tectonic setting in the central Mediterranean area (e.g., Mantovani et al. 2006, 2007a, b, 2009; Viti et al. 2006, 2009, 2011) suggests that the Adriatic plate (Adria hereafter) is stressed by the convergence of the confining plates (Africa, Eurasia and Anatolian-Aegean system) and tends to move roughly northward (Fig. 5).

This plate motion is accommodated by tectonic activity at the eastern (Hellenides, Dinarides), northern (eastern Southern Alps) and western (Apennines) boundaries of that plate, involving fairly different strain styles. Underthrusting of Adriatic lithosphere mainly occurs beneath the Hellenides (from the Ionian islands to Albania) and southern Dinarides (e.g., Louvari et al. 2001; Aliaj 2006; Benetatos and Kiratzi 2006; Kokkalas et al. 2006). Seismotectonic activity is highest in the Hellenic sector since such zone marks the collision zone between converging blocks (Adria and the Anatolian Aegean system), while in the Southern Dinarides tectonic activity is only due to the motion of Adria with respect to the almost fixed Carpatho-Pannonian system. The activation of the Cephalonia fault (e.g., Louvari et al. 1999) allows the relative motion between two Hellenic sectors, the Peloponnesus wedge, facing the Ionian oceanic lithosphere, and the Epirus, facing the Adriatic continental domain (Mantovani et al. 2006).

In the northern Dinarides the relative motion of Adria with respect to the adjacent structures is mainly accommodated by dextral transpression at the fault system recognized in Istria and Slovenia (e.g., Markusic and Herak 1999;

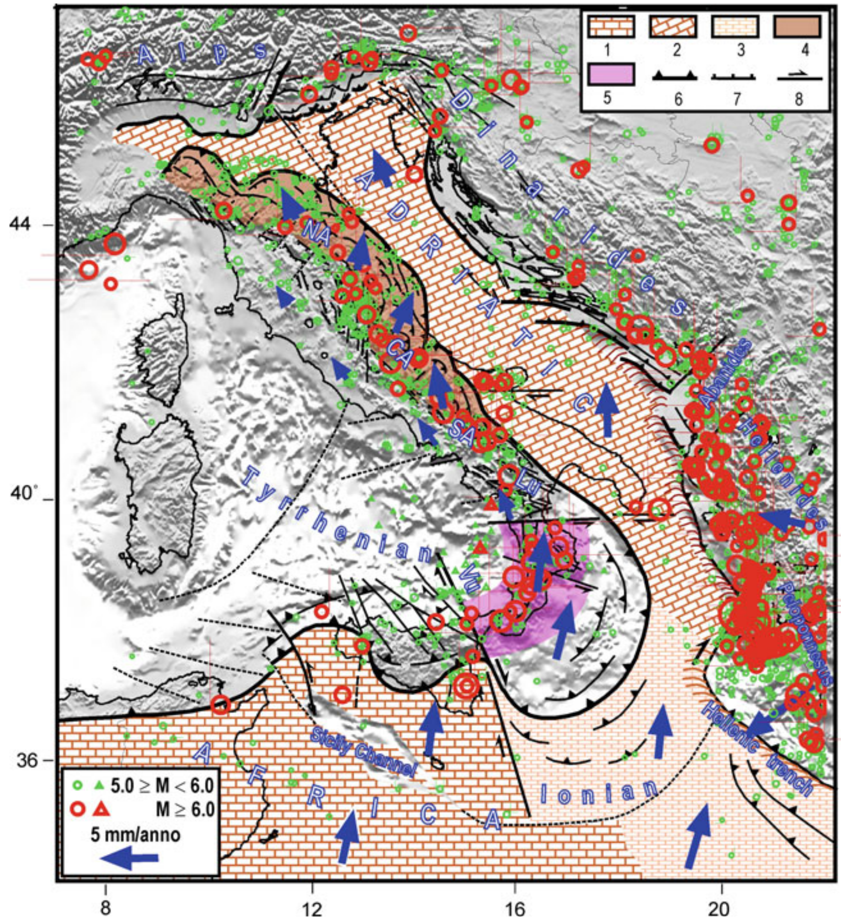


Fig. 5 Post-early Pleistocene kinematic and tectonic patterns in the central Mediterranean region (from Cenni et al. 2012; Mantovani et al. 2012). *1*, *2* African and Adriatic continental domains *3* Ionian oceanic domain *4* Outer sector of the Apennine belt carried by the Adriatic plate *5* Calabrian Arc *6–8* Major compressional, extensional and transcurrent tectonic features. *Blue arrows* show a tentative reconstruction of the Quaternary kinematic pattern with respect to Eurasia (from Mantovani et al. 2007b). *Circles* indicate earthquake epicentres in the period 1600–2013, taken from: Shebalin et al. (1974), Makropoulos and Burton (1981), Papazachos and Comninakis (1982), Comninakis and Papazachos (1986), Anderson and Jackson (1987), Jackson and McKenzie (1988), Papazachos and Papazachos (1989), Albini (2004), Guidoboni and Comastri (2005), Godey et al. (2006), Rovida et al. (2011), Makropoulos et al. (2012), Global CMT Catalog (Ekström et al. 2012); CATGR1900 at www.geophysics.geol.uoa.gr. *CA* Central Apennines; *Lu* Lucanian Apennines, *NA* Northern Apennines; *SA* Southern Apennines; *Vu* Vulcano-Syracuse fault system

Kuk et al. 2000; Poljak et al. 2000; Burrato et al. 2008). In the eastern Southern Alps, the Adriatic lithosphere underthrusts the Alpine edifice (e.g., Bressan et al. 2003; Galadini et al. 2005).

On the western side of Adria, mainly corresponding to the Apennine belt, the tectonic context is more complex (Fig. 5), mainly due to the fact that the outer sector of that chain is forced by belt-parallel compression (induced by the Adriatic plate) to separate from the inner Tyrrhenian side of the chain and to extrude laterally, at the expense of the adjacent Adriatic domain (Viti et al. 2006, 2011; Mantovani et al. 2009; Cenni et al. 2012). Such more mobile, deforming and uplifting part of the belt is constituted by the Molise-Sannio wedge (in the southern Apennines), the eastern side of the Lazio-Abruzzi carbonate platform (ELA), in the central Apennines, and the Romagna-Marche-Umbria (RMU) and Toscana-Emilia (TE) wedges, in the northern Apennines. The separation of those escaping wedges from the inner almost fixed belt is accommodated by extensional and sinistral transtensional deformation, mainly concentrated in the axial part of the chain, where a series of basins has developed in the Quaternary (e.g., Piccardi et al. 2006 and references therein). Compressional deformation develops at the outer front of the extruding wedges, where they overthrust the Adriatic domain (e.g., Scisciani and Calamita 2009). In the central Apennines, the decoupling between the outer ELA block and the western side of that platform is accommodated by two major SE-NW sinistral transtensional fault systems (L'Aquila and Fucino, e.g., Piccardi et al. 2006; Elter et al. 2012).

The outward extrusion (at the expense of the Ionian domain) and uplift of the Calabrian wedge is driven by belt-parallel compression (Mantovani et al. 2009). This interpretation is fairly consistent with the structural tectonic features evidenced by seismic surveys (Finetti 2005; Del Ben et al. 2008).

The relative motion between the outward extruding Calabrian wedge (at the expense of the Ionian domain, and the Molise-Sannio wedge (moving roughly NE ward, in connection with Adria) is accommodated by the system of NW-SE sinistral strike-slip faults recognized in the Lucanian Apennines (e.g., Catalano et al. 2004; Ferranti et al. 2009).

The motion of Adria is very slow during quiescent periods, while it locally accelerates during co-seismic and post-seismic phases, in response to major decoupling earthquakes at the eastern, western and northern periAdriatic boundaries.

Considering the tectonic context described above and the fact that the seismic activation of a periAdriatic sector may influence the probability of strong shocks in nearby sectors (Viti et al. 2003, 2012, 2013; Mantovani et al. 2008, 2010, 2012), one could expect to observe regularities in the time-space distribution of seismicity along the periAdriatic zones. This hypothesis is corroborated by the time patterns of seismicity at the main periAdriatic sectors for the period following 1400 (Fig. 6).

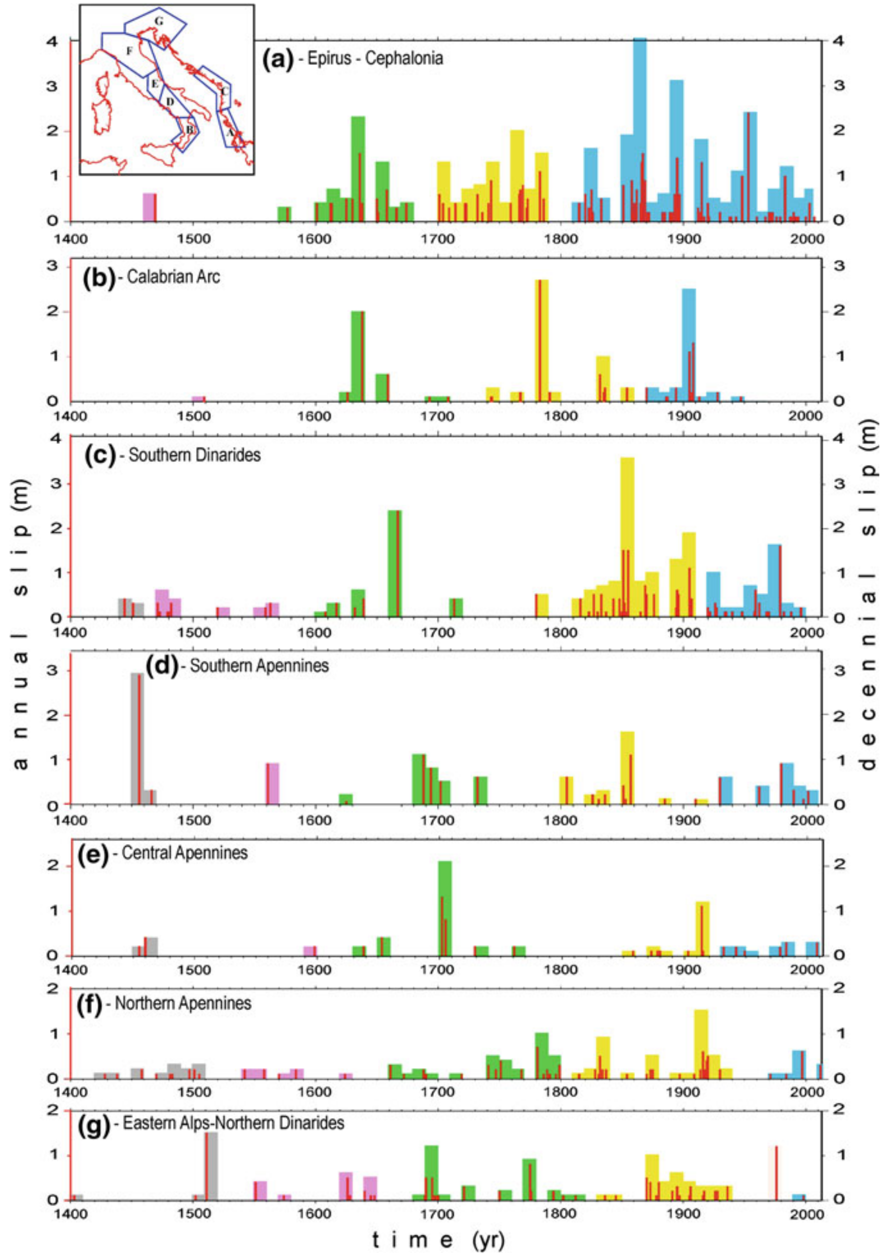


Fig. 6 Time patterns of major seismicity (M ≥ 5.5) in the main periAdriatic seismic zones since 1400 A.D. The geometries of the zones considered are shown in the inset. *Red bars* indicate the total seismic slip (meters) occurred during the related year, computed by the relation of Wells and Coppersmith (1994) between average slip and earthquake magnitude. The height of *vertical boxes* indicates the sum (meters) of seismic slips over the related decades. *Colours* help to recognize the presumed migrations of seismic phases from the southern to the northern periAdriatic zones (see text for comments). Seismicity data are listed in the Appendix along with references

In order to provide an information more representative of the effects that major decoupling earthquakes produce on local plate kinematics, the diagrams in Fig. 6 show the time pattern of the annual sum of seismic slips, computed by the Wells and Coppersmith (1994) relation:

$$\log_{10} u = -4.8 + 0.69\, M \tag{1}$$

where u is the average seismic slip (in meters) on the fault and M is the earthquake magnitude. The same diagram also aims at giving insights into the time concentration of seismic slips, by reporting the total seismic slip over intervals of ten years. In particular, this parameter may be useful to recognize how rapidly the surrounding structures may have been stressed by the effects of the triggering earthquakes (post-seismic relaxation), as discussed in Sect. 2.

The time patterns shown in Fig. 6 point out that in the periAdriatic zones seismicity is mostly discontinuous over time, with periods of high activity separated by almost quiescent phases. Furthermore, it may be recognized that seismic phases tend to progressively migrate over time from the southern to northern zones, through the eastern (Hellenides and Dinarides) and western (Apennines) boundaries of Adria, up to reach the northern compressional front (Eastern Alps) of that plate. In Fig. 6, the presumed migrating sequences are tentatively marked by different colours (grey, green, yellow and blue). One might suppose that the periAdriatic decoupling earthquakes involved in each sequence may have allowed the whole plate to make a further step (roughly 1–2 m) towards Europe.

The first presumed sequence (grey in Fig. 6) can only be recognized for the central and northern periAdriatic zones, where a significant increase of seismic activity took place, from about the middle of 15th century in Albania and Southern Dinarides, to the beginning of the 16th century in the northern Adriatic front. Since very low seismicity is documented in the Hellenides and Calabria before 1600 AD, it is not possible to recognize when this sequence may have started in such zones. Anyway, the comparison of the seismicity pattern that occurred since 1444 (Fig. 7a) and the one that took place in the previous period (Fig. 7b) points out the considerable increase of activity that the central and northern periAdriatic zones underwent after the occurrence of major seismic crises in the Albania-Southern Dinarides (1444–1451) and Southern Apennines (1456).

The quantification, by numerical experiments, of the effects of post-seismic relaxation induced by the strong 1456 earthquakes in the southern and central Apennines (Mantovani et al. 2012; Viti et al. 2013) indicates that such phenomenon may have influenced the occurrence of the major shock that took place in the northern Apennines roughly 2 years later (Upper Tiber Valley, 1458 M = 5.8). The seismic sequence cited above was followed in most periAdriatic zones by a long period of moderate activity (white bands in Fig. 6), when only few strong shocks occurred in the Albania-Southern Dinarides and Northern Apennines.

The first presumably complete sequence (green in Fig. 6) started with a considerable increase of seismic activity at the Hellenides during the first decades of the

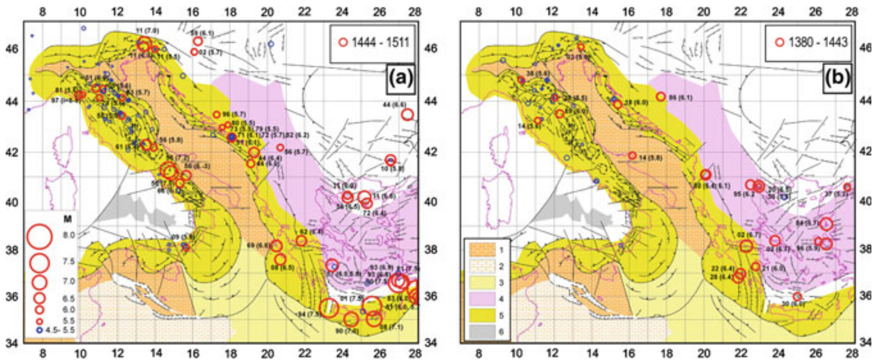


Fig. 7 Distribution of major shocks in the central Mediterranean area during the time interval 1444–1511 (**a**), presumably related to the first seismic sequence (*grey* in Fig. 6). In order to give information on how seismic activity during this phase was considerably stronger than the one occurred in the previous period, the seismicity pattern in the time interval 1380–1443 (**b**) is also reported. Symbols and data sources as in Fig. 4

17th century. This crisis was followed by a significant increase of seismic activity in all other periAdriatic zones, up to reach the northern front of Adria in the first half of the 18th century. In particular, the Calabrian Arc was hit by one of the major seismic crises (1638, M = 6.9, 7.0) of its known seismic history. It is worth noting that in the northern Apennines seismic activity that occurred during this phase was characterized by a fairly clear northward migration, as evidenced in the three pictures of Fig. 8.

At the northern Adriatic front, major seismic activity lasted until about the end of the 18th century, after which it underwent a drastic reduction for a relatively long period, until 1870.

The beginning of a new seismic sequence (yellow in Fig. 6) was marked by a drastic increase of seismic activity in the Hellenides in the last decades of the 18th century. In this case too, the Balkan crisis was accompanied by strong earthquakes in Calabria (1783, M = 7.0, 7.0, 6.6). Soon after the first crisis, a new seismic period occurred in the Hellenides, from 1815 to 1826, that was again followed by other major shocks in Calabria (1854, M = 6.2 and 1870 M = 6.1). That sequence then continued with several major events in the Albania-Southern Dinarides and Southern Apennines.

In the central Apennines, seismic activity was moderate for a relatively long period, until the occurrence of the strongest shock ever recorded in this zone (Fucino 1915, M = 7.0). This major decoupling event was then followed by a series of strong shocks in the northern Apennines in the following 5 years (1916–1920). As argued in some papers (Mantovani et al. 2010, 2012; Viti et al. 2012, 2013), the

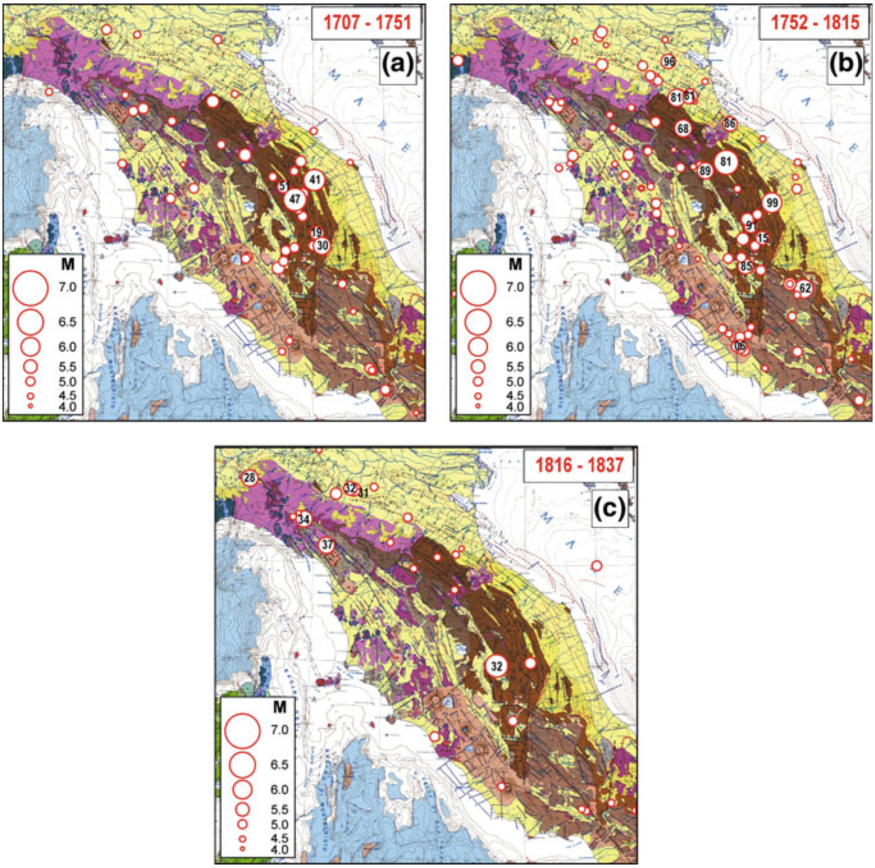


Fig. 8 Distribution of major earthquakes in the northern Apennines during the green sequence in Fig. 6. The three pictures point out the progressive northward migration of seismicity, during three consecutive periods, indicated in the frames. For the events with M ≥ 5.5 the year of occurrence is given. The underlying tectonic map is taken from Funiciello et al. (1981)

space-time distribution of major shocks during the above seismic sequence (1915–1920) is consistent with the tectonic implications of the proposed tectonic context in the Apennine belt (Viti et al. 2012, 2013). Furthermore, numerical modelling of the effects of the post-seismic relaxation induced by the 1915 Fucino and subsequent (1916–1920) strong earthquakes (Viti et al. 2012, 2013) shows that each event of such series just occurred when the respective source zone was reached by the highest values of the strain and strain rate perturbation induced by the previous shocks. Finally, the strain regime of the predicted post-seismic perturbations generally agrees with the style of seismic faulting recognized in the Apennine zones activated during the 1916–1920 sequence.

The last seismic sequence (blue in Fig. 6) started around 1850, with a period of very high activity (from about 1850 to 1872) in the Northern Hellenides, which was

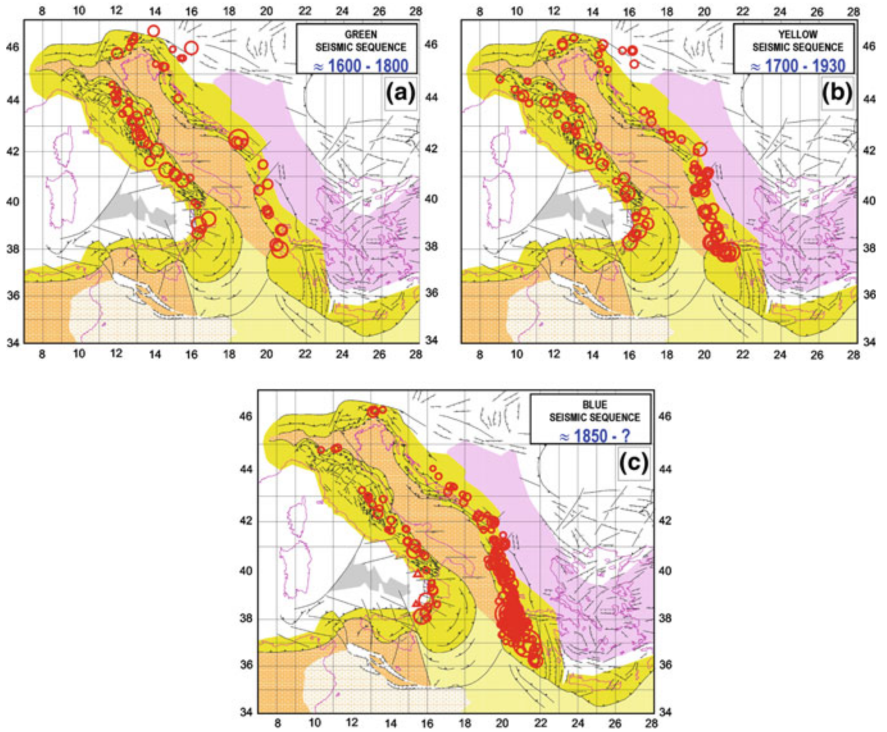


Fig. 9 Spatial distribution of seismicity during the last 3 sequences shown in Fig. 6 (*yellow*, *green* and *blue*). Data sources as in Appendix

soon followed by another crisis roughly lasting from 1885 to 1903. As in previous cases, these crises were accompanied by major earthquakes in Calabria (1870 M = 6.1, 1905 M = 6.9, 1908 M = 7.2). Subsequently, seismic phases underwent a progressive northward migration through the periAdriatic zones, up to reach the central sectors of the Dinarides and Apennines, while scarce seismicity has so far affected the northern zones. No major shocks (M > 5.5) have so far occurred in the northern Dinarides and only one major seismic crisis has affected the Eastern Alps (1976). Scarce seismic activity has also interested the northern Apennines, with only 3 moderate shocks (1971 M = 5.6 and 2012 M = 5.8, 5.9).

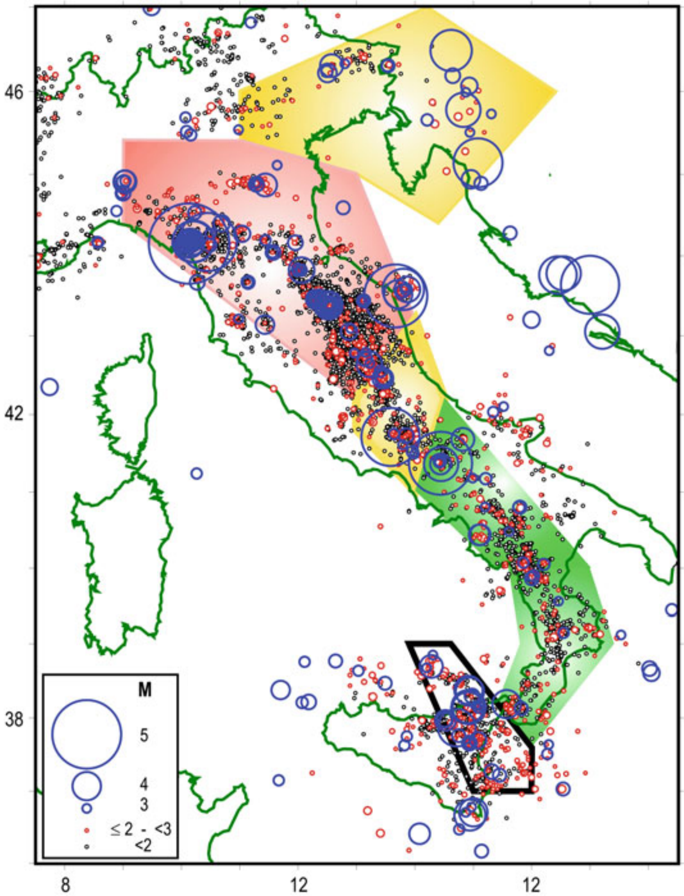
Further insights into the fact that the ongoing sequence has not yet undergone a full development may be derived from the space distribution of major earthquakes in the last three sequences (Fig. 9). The first two sequences involved a fairly homogeneous covering of most seismic periAdriatic zones, whereas the last sequence presents a very scarce covering of the northern zones.

Thus, if one could always rely on the fact that seismic activity in the periAdriatic zones is affected by a systematic tendency to progressively migrate from south to north, the evidence shown in Figs. 6 and 9 would indicate that the probability of hosting the next major shock is higher in the northern zones (northern Apennines, northern Dinarides and eastern Southern Alps) than in the southern zones (Calabria and Southern Apennines). As concerns the central Apennines, the recognition of the present probability of major shocks is not easy, since during the last sequence this zone has been affected by a number of earthquakes, but not as strong as the ones occurred in the previous sequences. So one cannot exclude that a further seismic activation of that sector will occur in the next future. Thus, an intermediate probability, higher than the one in the southern zones and lower than the one in the Northern Apennines, could tentatively be assumed for this zone. Furthermore, considering that in the proposed seismotectonic scheme the activation of the Northern Apennines is expected to precede major earthquakes in the northern Adriatic front, in line with what has happened in the known history, one might tentatively assume that at present the probability of hosting the next shock is higher in the northern Apennines than in the northern front of Adria.

A synthesis of the relative probabilities discussed above is shown in Fig. 10. It is opportune to clarify that the prediction here proposed only aims at providing a possible scale of priorities for eventual initiatives for risk mitigation and that no information is provided about the time of occurrence of the next event.

Notwithstanding that the relationships between strong earthquakes and the pattern of minor seismicity are not yet clear (e.g., Marsan 2005 and references therein), it may be useful to know the present level of such activity in the periAdriatic zones (Fig. 10). One major evidence in this pattern is that in the Northern Apennines, i.e. the zone here indicated as the most prone to the next strong earthquake, the number of minor events is much higher than in the other zones of the Italian peninsula. This proportion does not change significantly if larger thresholds of magnitude are considered (Fig. 10).

One could try some considerations about the possible implications of the above evidence. A high level of the so-called instrumental seismicity in a zone evidently indicates that such zone is actually undergoing a significant level of stress and strain, that is presumably accommodated by minor sliding at the faults which are most favorably oriented. The fact that such phenomenon is more evident in the Northern Apennines could support the hypothesis that at present such zone is the one undergoing the most intense stress. However, one must be aware that such evidence does not necessarily imply that the zone involved will be affected by a strong shock in the next future. For instance, it might occur that after a long series of minor sliding the fault involved reaches a configuration which inhibits any further sliding (e.g., Wesnousky 2006). This could considerably slowdown seismic activity even for a long time. On the other hand, one cannot obviously exclude that the fracture reaches a zone of favored sliding, causing a major shock (e.g., Marsan 2005).



Seismicity between 1-1-2013 and 28-2-2014 with h ≤ 30 Km			
	whole	M ≥ 2	M ≥ 3
Eastern Alps and Northern Dinarides	152	60	16
Northern Apennines	18608	1284	102
Central Apennines	1435	186	10
Southern Apennines	1097	197	20
Calabrian Arc	1345	164	7
Eastern Sicily	1335	296	21

Fig. 10 Relative probability of major earthquakes in the Italian zones considered in this study. *Red* indicates the zone with the highest expected probability (Northern Apennines), *orange* identifies the intermediate probability (Central Apennines and Eastern Alps) and *green* indicates the lowest probability (Southern Apennines and Calabria). No prediction is provided for Sicily. The *table* reports the number of minor shocks occurred in 2013 in the above zones. Data from ISIDe Working Group (INGV 2010)

5 Conclusions and Discussion

It is suggested that the next major earthquake (M ≥ 5.5) in the Italian peninsula will most probably be located in the northern part of the territory, with particular regard to the region here identified as Northern Apennines. This prediction is obtained by a deterministic approach, based on the expected short-term development (tens of years) of the proposed seismotectonic context. The model adopted provides that Adria, stressed by the convergence of the confining blocks, tends to move roughly northward. The development of this plate kinematics is rather complex in space and time, since displacement mainly accelerates locally, in response to major decoupling earthquakes in periAdriatic zones. Each shock triggers a perturbation of the strain field that, propagating through the plate, may increase the probability of seismic activation in the next sectors of the Adria boundary.

This interpretation may plausibly account for the time patterns of seismicity that has developed in the periAdriatic zones since 1400 A.D. In particular, it accounts for the fact that seismic energy release in each zone is mostly discontinuous, with main seismic phases separated by almost quiescent periods, and for the general tendency of main seismic phases to progressively migrate from south to north, through the eastern and western Adria boundaries, up to reach the northern front of the plate (eastern Southern Alps).

At least two presumably complete migration sequences, roughly 200 years long, may tentatively be recognized in the period considered. A further, still ongoing, sequence presumably started around the second half of the 19th century and has so far involved major seismic activations of the Hellenides, Calabria, Southern Dinarides, Southern Apennines and Central Apennines, while only few earthquakes have so far affected the northern zones (Northern Apennines, Northern Dinarides and eastern Southern Alps). This evidence might imply that the next step of the proposed seismotectonic pattern will most probably involve the seismic activation of fault systems located in the northern periAdriatic zones. The development of the previous sequences would suggest a higher probability for the Northern Apennines with respect to the Eastern Alps.

This prediction is consistent with the implications of two significant interrelations recognized between Italian and Dinaric-Hellenic zones, which suggest that at present the probability of strong earthquakes is relatively low in the Southern Apennines and Calabria. This prediction relies on the hypothesis that the seismic activation of such Italian zones is conditioned by the occurrence of major seismic crises in the Southern Dinarides and Hellenides respectively, where no significant precursory events have occurred in the last tens of years (Fig. 6 and Table 1).

An intermediate probability, comparable to that of the eastern Southern Alps, is proposed for the Central Apennines, where the release of seismic energy during the ongoing sequence has not reached the levels reached in previous sequences (Fig. 6).

On the basis of the evidence and arguments discussed in this work and in previous publications (Mantovani et al. 2010, 2012; Viti et al. 2012, 2013), we have tentatively defined the scale of priorities given in Fig. 10.

We are obviously aware that the reliability of the proposed prediction cannot easily be demonstrated, mainly due to the shortness and incompleteness of the seismic history now available, which only allows the recognition of few migration patterns in the periAdriatic zones. However, one should take into account that the approach here adopted is not only based on a mere empirical analysis of the seismic history, but relies on a deterministic scheme which is based on the expected short-term behaviour of a tectonic model inferred by a long and accurate analysis of a large amount of Earth Science data (e.g., Mantovani et al. 2006, 2009; Viti et al. 2006, 2011, 2012). Furthermore, it must be pointed out that geodetic observations (GPS) in the Italian region indicate that the present kinematic pattern of the Apennine belt is fairly similar to the one that may be deduced by the post-early Pleistocene deformation pattern (Cenni et al. 2012).

This study does not provide any prediction for some Italian seismic zones, such as Sicily, Apulia and Northwestern Italy, since for those zones we do not have sufficient information to afford hypotheses about the future short-term development of seismic activity (e.g., Mantovani et al. 2009). The tentative prediction synthetized in Fig. 10 is based on two main aspects, one is deterministic, relying on the knowledge of the ongoing tectonic setting and its possible connection with the spatio-temporal distribution of major earthquakes, and the other is mainly empirical, concerning the significant seismicity regularity patterns deduced by the analysis of the seismic histories of the zones involved. For the 3 zones mentioned above the second aspect is not available.

Concerning the deterministic aspect, some considerations about the present seismic hazard in Sicily can be tentatively made. As discussed earlier, the westward jump of the Anatolian-Aegean system (after 1939) has most probably strengthened E-W compression in the zone comprising the northern Ionian zone, the Calabrian Arc and the Hyblean block (including Sicily). This effect is expected to inhibit the outward extrusion of the Calabrian wedge, due to the presumed thickening and upward flexure of the Ionian domain. This hypothesis might explain the scarce seismic activity in Calabria since the middle of the last century (Fig. 4). On the other hand, the above compressional context could have favoured the northward escape of the Hyblean wedge, which would imply an increased probability of seismic activation of the main lateral guide of that extrusion, that is the Vulcano-Siracusa fault system, crossing the northeastern part of Sicily (Fig. 5).

However, since the jumps of the Anatolian-Aegean system are very rare tectonic events, with presumed recurrence times of several centuries (e.g., Ambraseys and Jackson 1998), it is not possible to recognize in the known seismic history eventual significant regularity patterns concerning the interaction of seismic sources in such kind of situations. Thus, not having any empirical confirmation of the expected tectonic processes, we cannot afford any reliable prediction about seismic activity of Sicily in the next future. In this regard, it could be worth noting that in the last decades of the previous century, i.e. the period that followed the westward jump of the Anatolian Aegean system, seismic activity in eastern Sicily has undergone a significant increase with respect to the previous period (Fig. 4). Furthermore, one could also note that the in the last year instrumental seismicity in eastern Sicily has been higher than in other zones (Fig. 10), except the northern Apennines.

A last consideration may be devoted to the fact that in January 2014 some earthquakes with an intermediate magnitude ($5.5 < M < 6.3$) occurred at the Cefalonia fault system, the zone of possible precursors of Calabrian earthquakes. This level of magnitude is low with respect to the events that have triggered strong earthquakes in Calabria (Table 1), but these signals may suggest the opportunity of improving the seismological and geodetic monitoring of the zones involved.

6 Possible Social Impact of the Proposed Prediction

On the basis of the past seismic history, one can reasonably suppose that in the next decades Italy will be hit by one or two major earthquakes. This implies that the problem of risk mitigation will primarily concern a limited part of the territory. This consideration, however, cannot be of much help if no information is available about which zones may be involved. Thus, any effort to get significant insights about the most probable spatial distribution of major earthquakes in the next future should be encouraged.

This work describes an attempt in this direction, carried out by exploiting the present knowledge on the ongoing seismotectonic setting in the central Mediterranean region and its possible connection with the time-space distribution of past major earthquakes. The results of this investigation suggest that the probability of strong shocks ($M > 5.5$) is presently highest in the Northern part of Italy, with particular regard to the Northern Apennines.

Notwithstanding the possible uncertainties, we think that the above prediction could be useful for practical purposes, such as the planning of the initiatives for seismic risk mitigation in Italy. In case of a successful prediction, the concentration of resources in the zones proposed would allow a not negligible improvement of safety. In case of failed prediction, the resources eventually employed in that area would not be wasted, since they would have allowed an improvement of safety in a zone which can plausibly be considered as most prone to next shocks. On the other hand, the adoption of a *blind* strategy (no priority zone) would imply that each of the numerous seismic areas of Italy would only benefit of a very limited portion of the available resources. Moreover, given the plausibility of the evidence and arguments presented in this work, we think that the probability of a successful result of the proposed strategy is higher than the ones of its failure.

The information provided in this work may also have implications for scientific activity. For instance the zones identified could become sites of specific monitoring (geodetic and seismological), aimed, for instance, at identifying eventual perturbations of the velocity and strain fields, possibly connected with impending shocks.

Appendix

List of earthquakes used for the diagrams of Fig. 6. M is the magnitude, Cat is the reference to seismic catalogues listed as follows: (1) Albini (2004); (2) Ambraseys (1990); (3) Global CMT Catalog (Ekström et al. 2012); (4) Working Group CPTI (2004); (5) Rovida et al. (2011); (6) Guidoboni and Comastri (2005); (7) ISIDe Working Group (INGV) (2010); (8) Karnik (1971); (9) Mariotti and Guidoboni (2006); (10) Seismological Catalogues of Greece; (11) Makropoulos et al. (2012); (12) Margottini et al. (1993); (13) Comninakis and Papazachos (1986); (14) Papazachos and Papazachos (1989); (15) Ribaric (1982); (16) Shebalin et al. (1974); (17) Stucchi et al. (2012); (18) Shebalin et al. (1998); (19) Toth et al. (1988).

Hellenides		
Date (y-m-d)	M	Cat
1278-2-25	6.6	17
1469	6.6	17
1577	6.2	17
1601-4-26	6.3	17
1612-5-26	6.3	17
1613-10-12	6.3	17
1625-6-28	6.5	17
1630-7-2	6.5	17
1636-9-20	7.2	10
1638-7-16	6.3	17
1650	6.5	14
1651-2-26	5.9	17
1658-8-24	6.7	17
1666-11	6.2	18
1674-1-16	6.3	17
1701-4-5	6.6	17
1704-11-22	6.4	17
1709	6.2	17
1714-9-8	6.3	17
1722-6-5	6.3	17
1723-2-22	6.3	17
1732-11	6.6	17
1736	6	10
1741-6-23	6.3	17
1743-2-20	6.9	10
1759-6-13	6.3	17
1766-7-24	6.6	17

(continued)

(continued)

Hellenides		
Date (y-m-d)	M	Cat
1767-7-22	6.7	17
1769-10-12	6.8	14
1772-5-12	6.1	18
1773-5-23	6.5	10
1783-3-23	6.6	17
1783-6-7	6.5	10
1786-2-5	6.5	17
1815	6.3	17
1820-2-21	6.6	17
1823-6-19	6.1	17
1825-1-19	6.7	17
1826-1-26	5.8	17
1833-1-19	6.5	14
1851-10-12	6.8	17
1858-4-5	6	10
1858-9-20	6.2	17
1858-10-10	6.4	17
1859-9-12	6	18
1860-4-10	6.4	18
1862-3-14	6.4	17
1862-10-4	6.2	17
1865-10-10	6.3	17
1866-1-2	6.6	17
1866-3-2	6.3	18
1866-12-4	6.4	17
1867-2-4	7.2	17
1869-8-14	6	18
1869-12-28	6.7	17
1871-4-9	5.8	17
1872-2-11	6	18
1883-6-27	5.5	10
1883-8	5.5	10
1885-12-14	6	10
1889-4-1	5.9	17
1890-5-21	5.9	17
1891-6-27	5.8	17
1893-6-14	6.6	17
1895-5-13	6.2	17
1895-5-14	6.5	17

(continued)

(continued)

Hellenides		
Date (y-m-d)	M	Cat
1895-5-15	6.2	17
1895-6-16	6.2	18
1896-2-10	5.5	18
1896-3-18	5.8	18
1897-1-17	6.6	17
1912-1-24	6.1	11
1914-11-27	5.9	11
1915-1-27	6.1	11
1915-8-7	6.3	11
1915-8-10	5.6	11
1915-8-10	6	11
1915-8-11	5.7	11
1915-8-19	5.9	11
1917-5-23	5.6	11
1920-10-21	5.6	11
1920-11-26	6	18
1920-11-29	5.5	18
1921-9-13	5.5	11
1930-11-21	5.8	18
1938-3-13	5.7	11
1939-9-20	5.5	11
1943-2-14	5.6	11
1948-4-22	6.5	11
1948-6-30	6.5	11
1953-8-9	5.9	11
1953-8-11	6.6	11
1953-8-12	7	11
1953-8-12	5.7	11
1953-8-12	5.9	11
1953-10-21	6.2	11
1960-11-5	5.7	11
1967-2-9	5.5	11
1970-7-2	5.8	11
1972-9-17	5.8	11
1973-11-4	5.8	11
1976-1-18	5.6	11
1979-11-6	5.6	11
1983-1-17	6.7	11
1983-1-19	5.5	11

(continued)

(continued)

Hellenides		
Date (y-m-d)	M	Cat
1983-3-23	6	11
1987-2-27	5.6	3
1988-5-18	5.5	3
1990-6-16	5.8	3
1992-1-23	5.6	3
1993-6-13	5.7	3
1994-2-25	5.5	3
2000-5-26	5.6	3
2003-8-14	6.2	3
2003-8-14	5.5	3
2007-3-25	5.7	3

Calabrian arc		
Date (y–m–d)	M	Cat
1509-2-25	5.6	5
1626-4-4	6	5
1638-3-27	7	5
1638-6-8	6.9	5
1659-11-5	6.6	5
1693-1-8	5.7	5
1708-1-26	5.5	5
1743-12-7	5.7	5
1744-3-21	5.7	5
1767-7-14	6	5
1783-2-5	7	5
1783-2-7	6.6	5
1783-3-28	7	5
1791-10-13	6	5
1832-3-8	6.6	5
1835-10-12	5.8	5
1836-4-25	6.2	5
1854-2-12	6.2	5
1870-10-4	6.1	5
1886-3-6	5.6	5
1887-12-3	5.5	5
1894-11-16	6.1	5
1905-9-8	7	5
1907-10-23	5.9	5
1908-12-28	7.1	5

(continued)

(continued)

Calabrian arc		
Date (y–m–d)	M	Cat
1913-6-28	5.7	5
1928-3-7	5.8	5
1947-5-11	5.7	5

South dinarides		
Date (y–m–d)	M	Cat
1237-3	6.2	18
1270-3	6.5	6
1273-3	6.5	10
1359	6	6
1380	6.1	17
1444	6.4	18
1451	6.1	18
1471	6.1	18
1472	5.7	18
1473-1-20	5.5	18
1479-10-20	5.5	18
1480-10-18	5.5	18
1482-2-15	6.2	18
1520-5-17	6	17
1559-6-24	6	1
1563-6-13	6.1	18
1608-7-25	5.6	17
1617	6.2	18
1632	6	17
1639-7-28	6.4	18
1667-4-6	7.5	18
1713-1-0	6.3	17
1780-9-21	6.5	18
1816	6.3	18
1823-8-7	5.7	18
1827-4-17	6.5	18
1830	5.6	18
1833-1-19	6.5	14
1837-10-4	5.5	18
1843-9-5	6.2	17
1843-9-26	5.6	18
1848	6.4	17
1850-4-13	5.6	17

(continued)

(continued)

South dinarides		
Date (y–m–d)	M	Cat
1851-1-20	6	18
1851-10-17	6.2	18
1851-10-17	6.6	17
1851-10-20	6.3	18
1851-12-29	5.5	18
1852-8-26	6.2	17
1853-12-11	5.7	18
1855-7-3	6.6	10
1855-7-5	6.8	18
1855-7-16	5.5	18
1855-8-14	5.5	18
1865-10-10	5.5	18
1869-1-10	5.6	18
1869-3-18	6	18
1869-4-14	5.5	17
1869-9-1	6.2	18
1870-9-28	6.5	17
1876-6-4	6.3	18
1876-6-5	5.6	18
1894-4-6	5.9	17
1895-5-14	5.5	18
1895-6-21	5.5	18
1895-8-6	6.2	17
1895-10-8	5.5	18
1896-2-10	5.9	17
1896-2-10	6.2	17
1905-6-1	6.6	18
1905-6-1	5.5	18
1905-6-3	5.5	18
1905-8-4	6	18
1905-8-6	5.5	18
1906-3-1	6.4	18
1907-8-1	5.7	18
1907-8-16	6.2	18
1920-11-29	5.6	13
1920-12-18	5.6	18
1921-3-30	5.6	11
1922-4-11	5.6	18
1926-12-17	5.8	18

(continued)

(continued)

South dinarides		
Date (y–m–d)	M	Cat
1926-12-17	5.8	18
1927-2-14	6	18
1934-2-4	5.6	18
1935-3-31	5.6	11
1940-2-23	5.5	18
1948-8-27	5.5	18
1958-4-3	5.6	18
1959-8-17	5.9	18
1959-9-1	6.2	18
1959-10-7	5.6	18
1962-3-18	6.2	18
1968-11-3	5.5	18
1969-4-3	5.5	11
1970-8-19	5.5	18
1979-4-15	7	2
1979-4-15	5.7	11
1979-5-24	6.4	18
1982-11-16	5.7	18
1988-1-9	5.7	18
1996-9-5	6	3

South apennines		
Date (y–m–d)	M	Cat
1273-12-18	5.8	5
1293-9-4	5.8	5
1361-7-17	6	5
1456-12-5	7.2	5
1456-12-5	7	6
1456-12-5	6.3	6
1466-1-15	6.1	5
1561-7-31	5.6	5
1561-8-19	6.8	5
1625-9-0	5.8	5
1688-6-5	7	5
1694-9-8	6.8	5
1702-3-14	6.5	5
1732-11-29	6.6	5
1805-7-26	6.6	5
1826-2-1	5.8	5

(continued)

(continued)

South apennines		
Date (y–m–d)	M	Cat
1831-1-2	5.5	5
1836-11-20	6	5
1851-8-14	6.4	5
1853-4-9	5.6	5
1857-12-16	7	5
1885-12-26	5.5	5
1910-6-7	5.7	5
1930-7-23	6.6	5
1962-8-21	5.7	5
1962-8-21	6.1	5
1980-11-23	6.9	5
1990-5-5	5.8	5
1990-5-5	5.5	5
1998-9-9	5.6	5
2002-10-31	5.7	5
2002-11-1	5.7	5

Central apennines		
Date (y-m-d)	M	Cat
1120-3-25	5.8	5
1170-5-9	5.6	5
1209	6	6
1315-12-3	5.6	5
1348-9-13	5.6	5
1349-9-9	5.9	5
1349-9-9	6	6
1349-9-9	6.6	5
1456-12-5	5.8	6
1461-11-27	6.4	5
1599-11-6	6	5
1639-10-7	5.9	5
1654-7-24	6.3	5
1703-1-14	6.7	5
1703-1-16	5.9	17
1703-2-2	6.7	5
1706-11-3	6.8	5
1730-5-12	5.9	5
1762-10-6	6	5
1859-8-22	5.5	5

(continued)

(continued)

Central apennines		
Date (y-m-d)	M	Cat
1874-12-6	5.5	5
1879-2-23	5.6	5
1881-9-10	5.6	5
1904-2-24	5.6	5
1915-1-13	7	5
1916-11-16	5.5	5
1933-9-26	6	5
1943-10-3	5.8	5
1950-9-5	5.7	5
1979-9-19	5.9	5
1984-5-7	5.9	5
1984-5-11	5.5	5
2009-4-6	6.2	5

North apennines		
Date (y-m-d)	M	Cat
1269-9	5.6	5
1277	5.6	5
1279-4-30	5.6	5
1279-4-30	6.3	5
1293-3	5.6	5
1298-12-1	6.2	5
1328-12-1	6.4	5
1352-12-25	6.4	5
1353-1-1	6	6
1389-10-18	6	5
1428-7-3	5.5	5
1438-6-11	5.6	5
1458-4-26	5.8	5
1470-4-11	5.6	5
1481-5-7	5.6	5
1483-8-11	5.7	5
1497-3-3	5.9	6
1501-6-5	6	5
1505-1-3	5.6	5
1542-6-13	5.9	5
1558-4-13	5.8	5
1570-11-17	5.5	5
1584-9-10	5.8	5

(continued)

(continued)

North apennines		
Date (y-m-d)	M	Cat
1624-3-19	5.5	5
1661-3-22	6.1	5
1672-4-14	5.6	5
1688-4-11	5.8	5
1690-12-23	5.6	5
1719-6-27	5.5	5
1741-4-24	6.2	5
1747-4-17	5.9	5
1751-7-27	6.3	5
1768-10-19	5.9	5
1781-4-4	5.9	5
1781-6-3	6.4	5
1781-7-17	5.6	5
1786-12-25	5.6	5
1789-9-30	5.8	5
1791-10-11	5.5	5
1796-10-22	5.6	5
1799-7-28	6.1	5
1815-9-3	5.5	5
1828-10-9	5.8	5
1831-9-11	5.5	5
1832-1-13	6.3	5
1832-3-13	5.5	5
1834-2-14	5.8	5
1837-4-11	5.8	5
1854-2-12	5.6	5
1870-10-30	5.6	5
1873-3-12	6	5
1875-3-17	5.9	5
1897-9-21	5.5	5
1909-1-13	5.5	5
1914-10-27	5.8	5
1916-5-17	6	5
1916-8-16	6.1	5
1916-8-16	5.5	5
1917-4-26	5.9	5
1918-11-10	5.9	5
1919-6-29	6.3	5
1920-9-7	6.5	5

(continued)

(continued)

North apennines		
Date (y-m-d)	M	Cat
1930-10-30	5.8	5
1971-7-15	5.6	5
1984-4-29	5.7	5
1997-9-26	5.7	5
1997-9-26	6	5
1997-10-6	5.5	5
1997-10-14	5.7	5
2012-5-20	5.9	7
2012-5-29	5.8	7

Eastern Alps–Northern dinarides		
Date (y-m-d)	M	Cat
1323	6	5
1348-1-25	7	5
1403-9-6	5.6	5
1502-3-26	5.7	18
1511-3-26	7	5
1511-6-25	5.6	17
1511-8-8	6.3	18
1551-3-26	6.3	18
1574-8-14	5.6	5
1626-7-3	6.5	18
1628-6-17	5.6	4
1640	6	4
1645	5.6	4
1648	5.7	18
1689-3-10	5.6	4
1690-12-4	6.5	5
1695-2-25	6.5	5
1697-3-15	5.6	4
1699-2-11	5.6	4
1700-7-28	5.6	5
1721-1-12	6.1	5
1750-12-17	5.9	18
1775-10-13	6.8	19
1776-7-10	5.8	5
1794-6-7	6	5
1802-1-4	5.6	18
1812-10-25	5.7	5

(continued)

(continued)

Eastern Alps–Northern dinarides		
Date (y-m-d)	M	Cat
1836-6-12	5.5	5
1845-12-12	5.7	18
1870-3-1	6.4	18
1870-3-1	5.6	17
1873-6-29	6.3	5
1878-9-23	5.6	17
1880-11-9	6.3	18
1891-6-7	5.9	5
1895-4-14	6.2	5
1897-5-15	5.6	5
1905-12-17	5.6	18
1906-1-2	6.1	18
1916-3-12	5.6	5
1917-1-29	5.8	4
1926-1-1	5.9	5
1928-3-27	5.8	5
1936-10-18	6.1	5
1976-5-6	6.5	5
1976-9-11	5.6	5
1976-9-15	5.9	5
1976-9-15	6	18
1976-9-15	6	5
1998-4-12	5.7	3

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Earthquakes and Their Impact on Society
D'Amico, S. (Ed.)
2016, XXIV, 706 p., Hardcover
ISBN: 978-3-319-21752-9