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Tectonics and Seismicity in the periAdriatic Zones: Implications for Seismic Hazard in Italy

Enzo Mantovani, Caterina Tamburelli, Daniele Babbucci, Marcello Viti and Nicola Cenni

Abstract

The recognition of the seismic zones most prone to next major earthquakes in Italy would considerably help the choice of the most efficient prevention plan. This work describes an attempt to gain reliable information about that problem by exploiting the knowledge about the short-term development of the ongoing tectonic processes in the study area and its influence on the spatio-temporal distribution of major shocks. In the periAdriatic zones, such distribution is connected with the progressive northward displacement of the Adria plate, that is controlled by the progressive activation of the decoupling fault systems in the surrounding belts (Dinarides, Apennines and Eastern Southern Alps). The reliability of this hypothesis is evaluated by analysing the seismic histories of the periAdriatic zones. The regularity patterns that are tentatively recognised in such histories are used to identify the most probable location of next major shocks. Further insights into the present seismic hazard in the Southern Apennines and Calabria are tentatively inferred from tectonic connections between these regions and other periAdriatic zones, suggested by the seismic histories in the last 2–4 centuries and the geodynamic/tectonic context in the central Mediterranean area.

Keywords: seismic hazard, tectonics, Apennines, Italy, deterministic approach

1. Introduction

It is well known that seismic activity in the periAdriatic zones (**Figure 1**) is related to the interaction of the Adriatic plate (Adria hereafter) with the surrounding belts (**Figure 2**).

Stressed by the convergence of the confining structures, Adria tries to move roughly northward [10–12, 14–16].

This gradual displacement is allowed by the activation of the decoupling fault systems located along the lateral boundaries of Adria (Dinarides and Apennines) and in the northern front of that plate, in the Eastern Southern Alps. The central and southern Dinarides and the Eastern Southern Alps are characterised by thrust faults while a dextral transpressional regime prevails in the northern

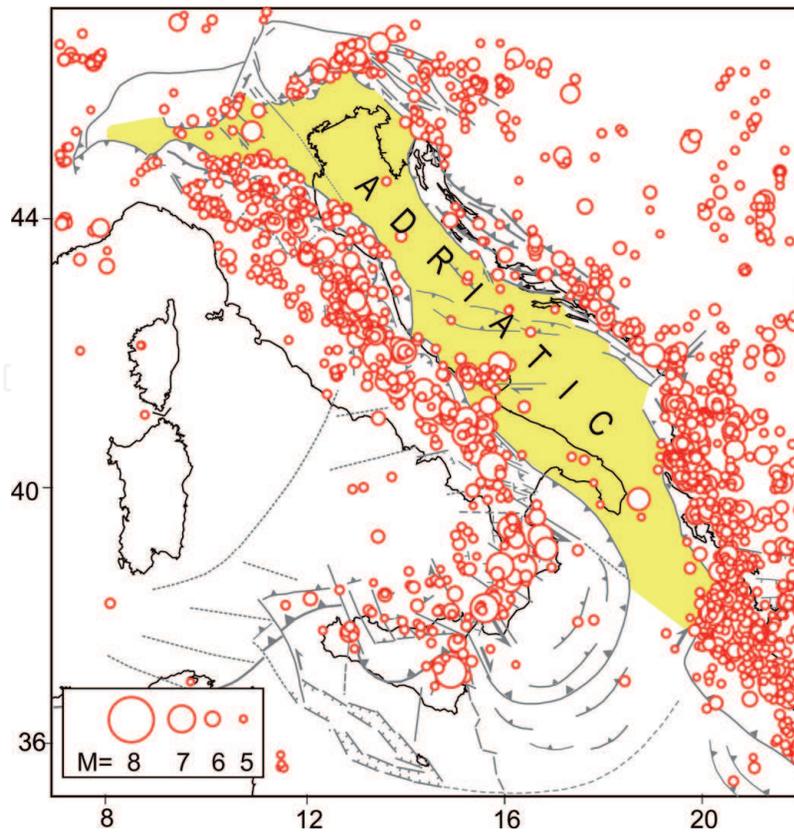


Figure 1.
Major earthquakes (red circles, $M \geq 5$) since 1000 A. D in the periAdriatic zones [1–9].

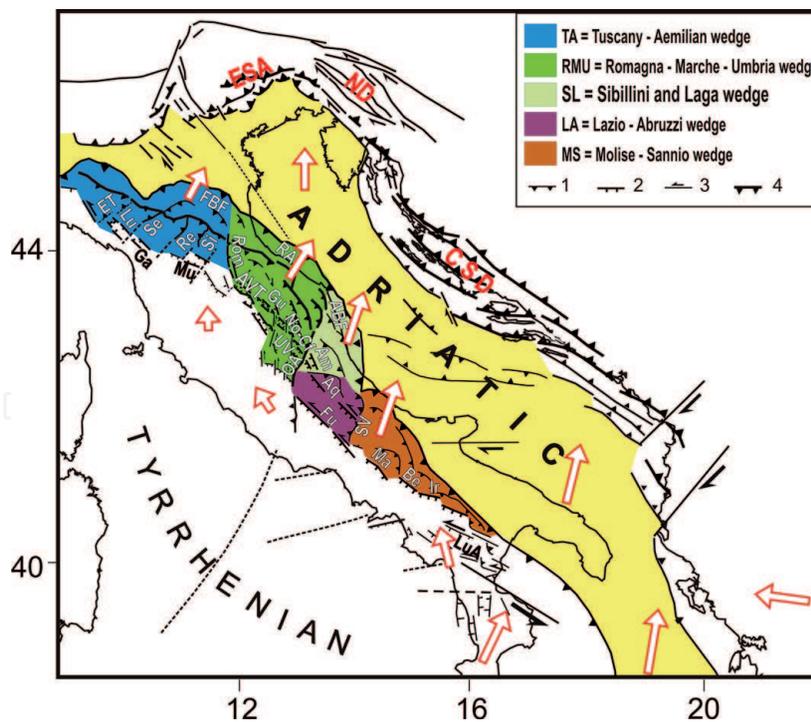


Figure 2.
Tectonic sketch of the Adriatic region (e.g., [10–12]). The main wedges in the eastern sector of the Apennine belt are evidenced by colours (inset). See text for explanations. The proposed kinematic pattern with respect to Eurasia [13, 14] is indicated by red empty arrows. 1) Compressional, 2) extensional 3) transcurrent features, 4) Outer fronts of Neogenic belts. Am = Amatrice fault system, Aq = L'Aquila fault system, AVT = Alta Valtiberina trough, CSD = Central-Southern Dinarides; ESA = Eastern Southern Alps; ET = Enza-Taro thrust, FBF = Ferrara buried folds, Fu = Fucino fault system; Ga = Garfagnana, Lu = Lunigiana, LuA = Lucanian Apennines, Ma, Be, Ir = Matese, Benevento and Irpinia fault systems, ND = Northern Dinarides, No-Cf-Gu = Norcia-Colfiorito-Gubbio fault system; OV = Olevano-Antrodoco-Sibillini transversal thrust, RA = Rimini-Ancona thrust front, Re = Reno thrust, Rom = Romagna fault system, Se = Secchia thrust, Si = Sillaro thrust, SV = Sangro-Volturno oblique thrust, UV = Umbra valley.

Dinarides e.g., [17–21]. The decoupling mechanisms along the western Adria boundary (Apennines) are more complex [10–12, 16], due to the presence of a shallow crustal structure (eastern sector of the chain, coloured in **Figure 2**), that is moving independently from Adria and the western (Tyrrhenian) sector of the belt. This tectonic/kinematic context has been determined by the fact that in the most recent evolution (Quaternary) the outer chain, stressed by Adria, has undergone longitudinal shortening, accommodated by major deformations:

- Strong uplift, recognised in various sectors of the chain [22–25].
- Formation of arcs, as the Campania-Lucania and the Matese-Benevento in the Southern Apennines (see [12] and references therein), the Gran Sasso in the Central Apennines [26, 27] and the Emilian and Ferrara buried folds in the Northern Apennines [28]. This deformation is also suggested by the transition from a cylindrical to a non-cylindrical (arcs) geometry of the orogenic accretion e.g., [28].
- The zones of interaction between the main belt sectors are characterised by transversal/oblique thrusts, as the Olevano-Antrodoco-Sibillini Mts. and the Sangro-Volturno [26, 29, 30].
- Roughly NE ward extrusion of major wedges, with particular regard to the Molise-Sannio (MS) and the Romagna-Marche-Umbria (RMU). This process is compatible with a large amount of geological evidence reported by Viti et al. [12] and references therein).

The divergence between the MS and RMU escaping wedges with respect to the inner less deformed belt has caused the formation of extensional and transtensional fault systems along the axial part of the chain, where a number of troughs has developed. Roughly NW-SE sinistral transtensional and transpressional faults developed in the Lucania Apennines e.g. [31–34]. Extensional faults are recognised in the Irpinia, Benevento and Matese zones, along the inner side of the MS wedge e.g., [35, 36]. The L'Aquila and Fucino transtensional fault systems allow the relative motion between the Lazio-Abruzzi (LA) wedge and the inner belt [26, 37–40]. The decoupling of the RMU wedge from the inner belt is accommodated by the Norcia-Colfiorito-Gubbio-Alta Valtiberina extensional and transtensional fault system and the parallel Umbra Valley trough (e.g., [41–43] and references therein). The simultaneous development of uplift and extensional features in the belt cannot easily be explained without assuming belt-parallel compression as driving force.

The occurrence of several major earthquakes in the Romagna Apennines reveals the presence of an important roughly S-N fault system (Rom in **Figure 2**, [44] and references therein, [42, 45]). This discontinuity allows the RMU wedge to decouple from the Tuscany-Emilia Apennines sector that is not parallel to the Adria plate.

Another evidence consistent with the longitudinal compressional regime in the northernmost Apennines is the presence of transverse thrust faults, as the Sillaro, Reno, Secchia and Enza-Taro faults [23, 46, 47].

The kinematic field that is suggested by the Quaternary deformation pattern in the Apennine belt [11, 48, 49] is compatible with the present displacement field, inferred from geodetic GPS data e.g., [11, 50, 51], which indicates that the outer Adriatic sector of the Apennine chain is moving faster (4–5 mm/y) and more northward with respect to the inner belt (about 1 mm/y).

2. Short-term kinematics of Adria and spatio-temporal distribution of seismicity in the surrounding belts

In the short-term the northward displacement of Adria does not develop continuously over time. Each seismic decoupling along the Adria lateral boundaries (Dinaric and Apennine belts) triggers the acceleration of the involved Adriatic sector e.g., [52–54] These local accelerations induce an increase of stress at the other still blocked Adria boundaries, where consequently the probability of earthquake occurrence gets higher. When such stressed zones are then affected by major shocks, the acceleration involves more northern zones of Adria up to reach the thrust front of Adria in the Eastern Southern Alps.

In order to check the above seismotectonic interpretation, we have divided the periAdriatic boundary zones in a number of sectors (**Figure 3**). The eastern lateral boundary of Adria includes the Central-Southern Dinarides (CSD in **Figure 4**), and the Northern Dinarides (ND). The western lateral boundary (Apennine belt) is divided in more sectors, being characterised by a more complex tectonic setting, as discussed in the previous section. The Southern Apennines (SA) are mainly characterised by extensional faulting. In the Central Apennines (CA) transtensional decoupling fault systems (L'Aquila and Fucino) prevail. The Northern Apennines are divided in various sectors, due to their complex tectonic setting, with particular regard to the Romagna-Marche-Umbria wedge (RMU). The southern part of the western RMU boundary (Norcia-Colfiorito-Gubbio fault system, RMUWB), is mainly characterised by extensional faults. Considering the peculiar seismotectonic role of the Northern RMU wedge, its boundaries, i.e. the Rimini-Ancona thrust front (RA), the Romagna fault (Rom) and the Alta Valtiberina trough (AVT), are taken as three independent zones. The Emilia Apennines (EM) is the belt sector that lies just north of the RMU wedge. The last sector in **Figure 4** (ESA-ND) is the zone where the Adria plate underthrusts the Eastern Southern Alps.

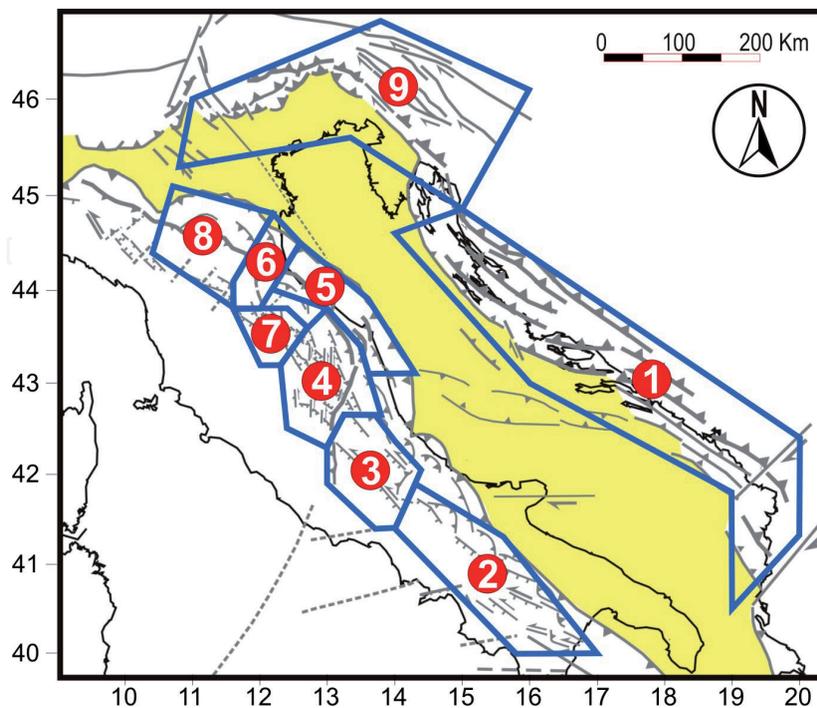


Figure 3. Geometries of the periAdriatic boundary zones adopted for determining the seismicity patterns shown in **Figure 4**. 1) Central-Southern Dinarides (CSD in **Figure 4**), 2) Southern Apennines (SA), 3) Central Apennines (CA), 4) Southern part of the western boundary of the RMU wedge (RMUWB), 5) Rimini-Ancona thrust front (RA), 6) Romagna fault system (Rom), 7) Alta Valtiberina trough (AVT), 8) Emilia Apennines (EM), 9) Eastern Southern Alps and Northern Dinarides (ESA-ND).

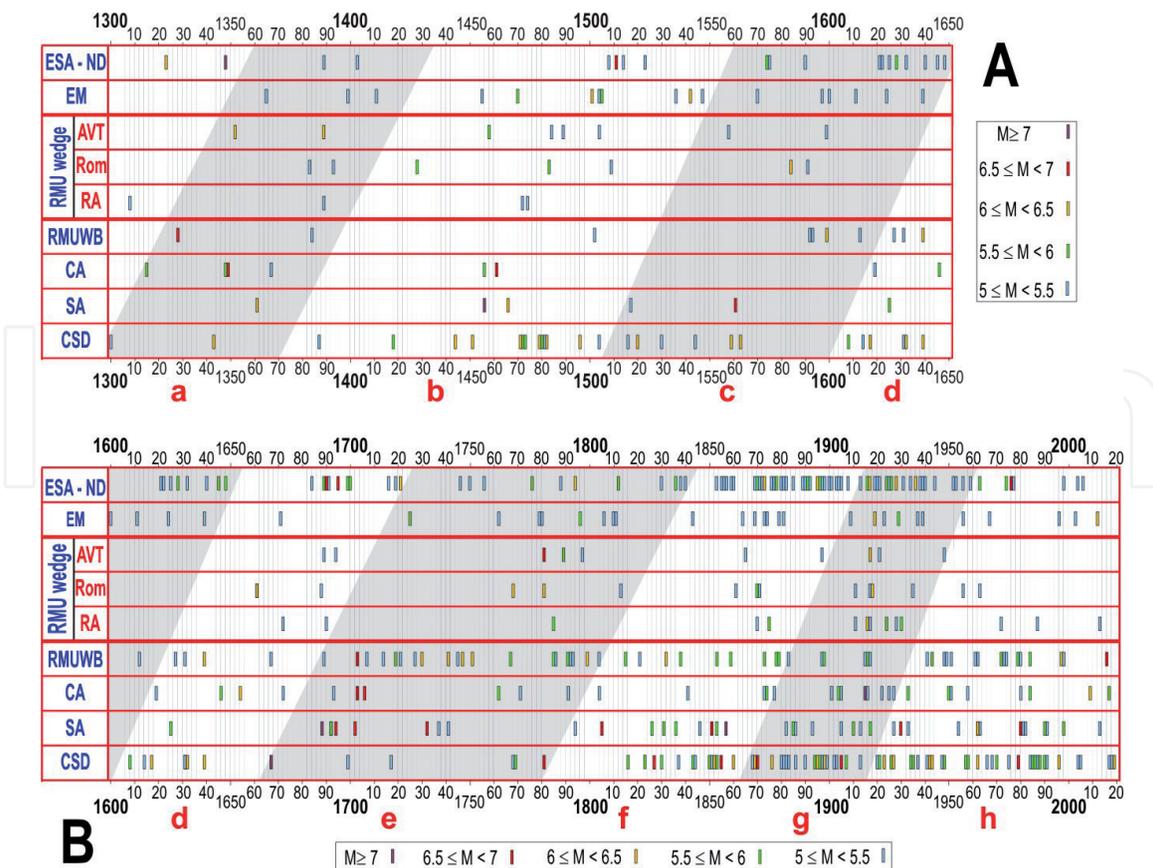


Figure 4.
 (A, B) Time patterns of seismic activity in the periAdriatic zones. AVT = Alta Valtiberina trough, CA = Central Apennines, CSD=Central-Southern Dinarides, ESA-ND = Eastern Southern Alps and Northern Dinarides, EM = Emilia Apennines, RA = Rimini-Ancona thrust front, RMUWB=Southern western boundary of the RMU wedge, Rom = Romagna fault system, SA = Southern Apennines. Earthquakes are indicated by bars with colours related to magnitude (scale in A and B). Sources of seismicity data in the caption of Figure 1. The grey and white bands tentatively include the events that are supposed to belong to the presumed migrating sequences, identified by letters (a-h). The geometries of the zones considered and the spatial distribution of major shocks in the various sequences are shown in the Figures 3 and 5 respectively.

In the seismicity time patterns shown in Figure 4, we tentatively recognise the following peculiar features:

- In the zones considered, most intense seismicity tends to concentrate in short periods (crises), separated by longer phases of lower activity.
- The crises tend to occur later and later as the zones involved are located more and more to the north, delineating a sort of migrating pattern (seismic sequence).
- A number of sequences may be recognised in the period considered, as tentatively evidenced by grey and white bands and letters (from a to h) in Figure 4.
- The time development of the proposed sequences tends to occur in two phases. During the first phase, seismicity mainly affects the southern and central Dinarides, the central and southern Apennines and the western extensional boundary of the RMU wedge (the Norcia-Colfiorito-Gubbio fault system). This phase generally involves several shocks of $M \geq 5.0$ in each zone and generally lasts some tens of years.
- In most cases, the second phase starts with a crisis in the Romagna decoupling fault system, followed (within 10–20 years) by the activation of the inner

(Alta Valtiberina trough) and outer (Rimini-Ancona thrust) boundaries of the northern RMU wedge.

- Then, seismic activity mostly involves the main fault systems in the Emilia Apennines, the Eastern Southern Alps and the Northern Dinarides, over periods of about one-two decades.
- Major earthquakes at the northern Adria front mostly occurred some years after the main seismic decouplings around the northern RMU wedge (**Figure 4**). This tendency is consistent with the hypothesis that the release of the RMU wedge favours the acceleration of the northern Adria domain [11, 42].

The spatial distribution of the shocks in the 8 sequences evidenced in **Figure 4** is shown in **Figure 5**.

In most of the proposed sequences seismic activity took place in all periAdriatic zones. Moreover, one could note that when a zone is characterised by low seismicity, in the following sequence such zone is often characterised by intense earthquakes. For example, in the sequence **c** the Central Apennines did not experience any event with $M \geq 5.0$ while strong earthquakes (1646 $M = 5.9$, 1654 $M = 6.3$) hit that zone in the subsequent sequence. In the Southern Apennines, after a period of low activity from 1562 to 1687 (only one earthquake with $M \geq 5.0$ in the sequences **c** and **d**), a phase of intense seismicity took place in the following sequence **e** (1688 $M = 7.1$, 1692 $M = 5.9$,

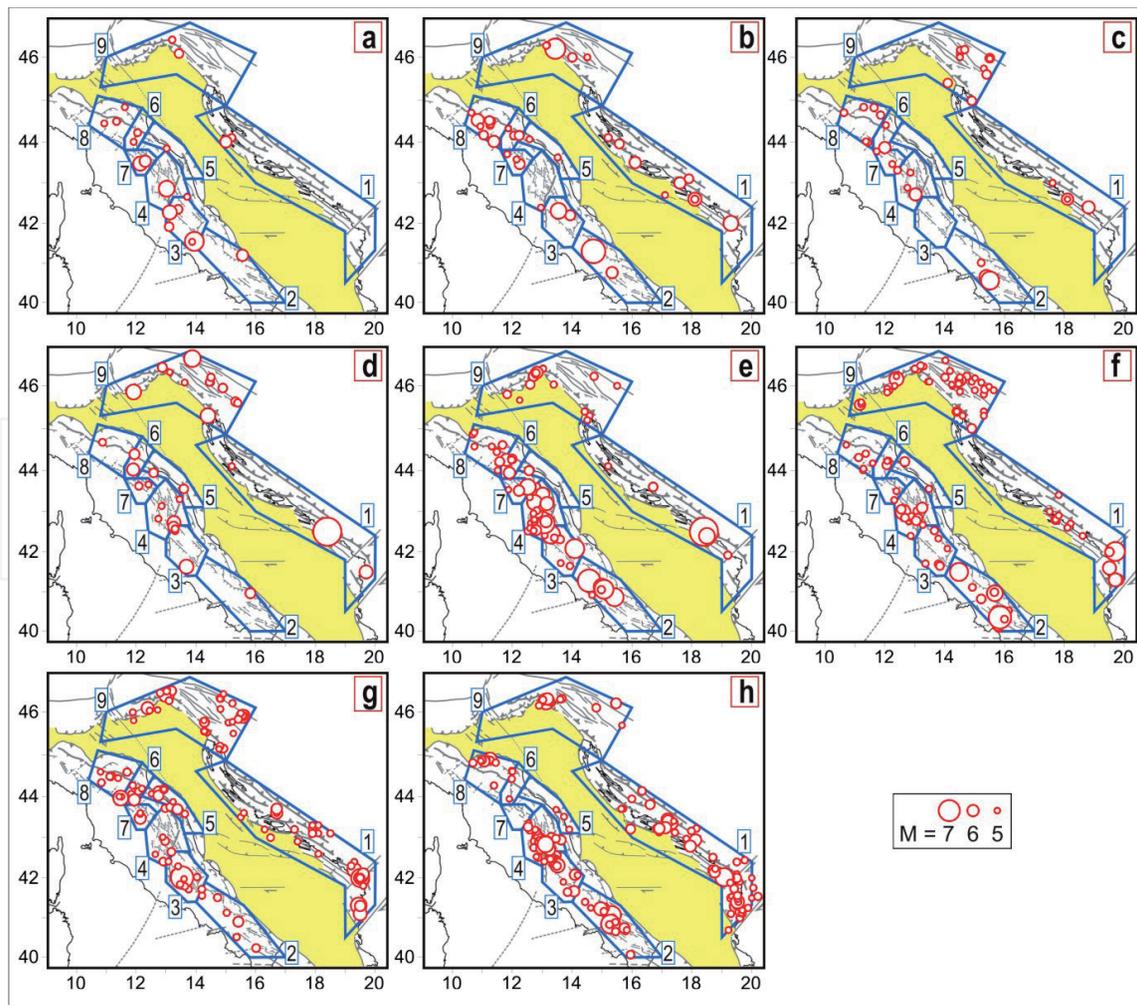


Figure 5. Spatial distribution of major ($M \geq 5.0$) earthquakes in the seismic sequences tentatively evidenced in **Figure 4**. Numbers as in **Figure 3**.

1694 M = 6.7). The strong 1915 Fucino earthquake (M = 7.1, sequence **g**) took place after a sequence (**f**) characterised by relatively low seismicity (few events with $M \leq 5.5$).

3. Some remarks on the Apennine zones most prone to the next strong earthquakes

Taking into account the regularity patterns that we tentatively recognise in the seismic sequences so far developed (**a-g** in **Figure 4**), we try to gain insights into how the last, still ongoing, sequence (**h** in **Figure 4**) might develop in the next future. In this regard, it must be considered that the first phase of that sequence has so far involved several earthquakes in the Southern and Central Dinarides and the Southern and Central Apennines. The acceleration of southern Adria triggered by such seismic decouplings has presumably stressed and deformed the RMU wedge, increasing its tendency to separate from the inner belt. This hypothesis may explain why a number of major extensional shocks (1979 M = 5.8, 1984 M = 5.6, 1997 M = 6.0, 5.7, 5.6, 5.5, 2016 M = 6.2, 6.1, 6.6, [7]) occurred along the western border of the RMU wedge (Norcia-Colfiorito-Gubbio fault system). The NE ward acceleration of the southern RMU wedge may have emphasised stresses (and thus seismic hazard) at the northern boundaries of that wedge (Romagna fault, Alta Valtiberina trough and Rimini-Ancona thrust front). Thus, one could expect that the present seismic hazard in such zones is higher than in the other Apennine fault systems. This hypothesis is also suggested by the fact that the last significant earthquakes ($M \geq 5.3$) in the above zones occurred about 100 years ago, i.e. a quiescence longer than the previous ones (**Figure 4**).

Another zone where tectonic load may currently be high is the Emilia Apennines and the related buried folds (**Figure 2**), since such structures, including the Mugello trough, have been stressed by the push of the RMU wedge during the last tens of years. The above hypothesis is consistent with the fact that intense earthquakes (2012, M = 6.1, 5.9) recently occurred in the Ferrara buried folds (lying outside the Emilian Apennines) and that moderate seismicity (M = 4.5) affected the Mugello trough on December 2019.

The kinematic field delineated by geodetic data [11, 50, 51] suggests that the separation between the inner and outer Apennine belts is developing at rates of about 3–4 mm/y, which implies that a displacement of about 30–40 cm has been accumulated since the last activations of the fault systems surrounding the northern RMU wedge (about 100 years). This displacement is comparable to the fault slip associated with a M = 5–6 earthquake e.g., [55].

4. Present seismic hazard in the Southern Apennines: further evidence from a seismotectonic correlation

Further information on the present seismic hazard in the Southern Apennines could be inferred from a correlation that has been recognised between the major earthquakes in that zone and the ones in the Southern Dinarides [56–61].

The possibility that intense seismic activity in the Southern Apennines may be influenced by the occurrence of major shocks in the Southern Dinarides has been first suggested by the fact that the strong April 1979 Montenegro event (M = 6.9) was followed by the strong November 1980 Irpinia earthquake (M = 6.8) in the Southern Apennines (**Figure 6**). The idea that the above correspondence may be a systematic phenomenon was then suggested by the fact that in the last two centuries similar correspondences occurred other times (**Figure 6B**). From the list of events given in

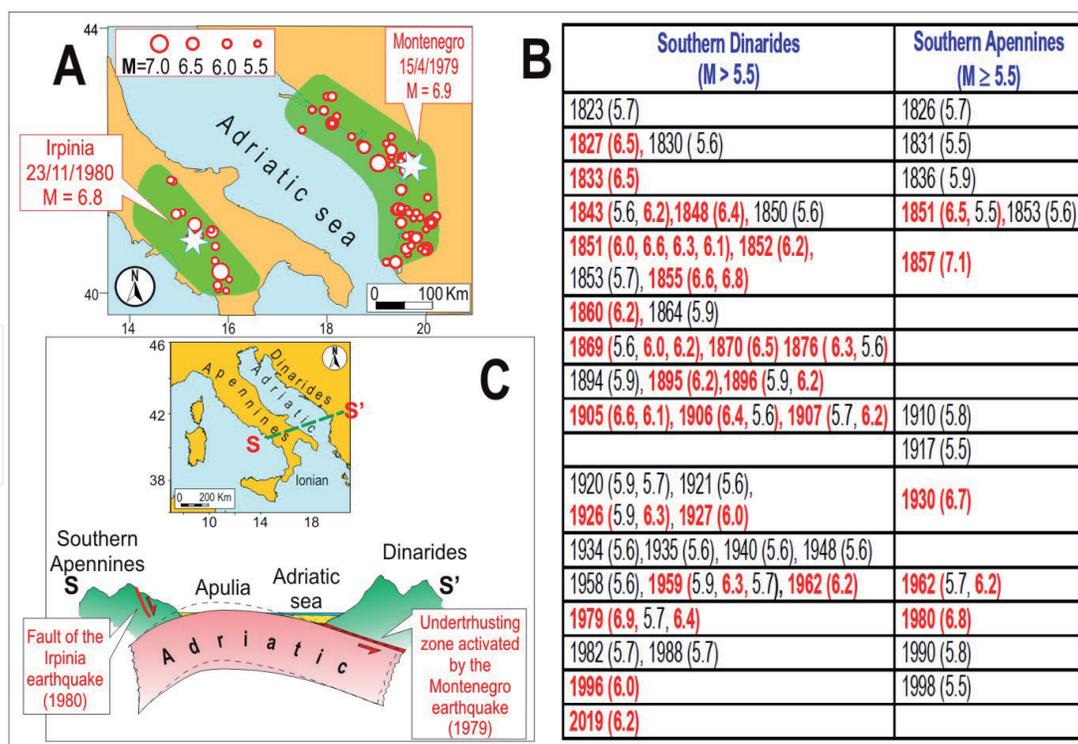


Figure 6.

A) Geometry of the zones implied in the presumed interrelation between Southern Dinarides-Albanides and Southern Apennines and location of the earthquakes given in the table. The stars indicate the locations of the 1979 and 1980 earthquakes in Montenegro and Irpinia. B) List of the major seismic events occurred since 1810. The events with $M \geq 6.0$ are in red. Seismicity data as in Figure 1. C) Structural sketch, through a transversal section in the southern Adriatic area (S-S'), evidencing the vertical flexure of the Adriatic lithosphere overthrust by the Dinaric belt, on one side, and plunged under the Apennine belt, on the other side (e.g., [62]). The vertical scale is exaggerated in order to make more evident the possible effect of a seismic slip (red arrow) along the subduction fault beneath the Dinaric belt. The dashed lines indicate the presumed profile of the Adriatic lithosphere before a seismic slip in the Southern Dinarides.

this figure, one can note that in the period considered all the shocks with $M \geq 6.0$ in the Southern Apennines have been preceded within few years (less than 5) by one or more earthquakes with $M \geq 6$ in the Southern Dinarides. The above correspondence does not worsen significantly even if a lower threshold ($M = 5.5$) is considered, given that only one of the 15 Southern Apennine events failed to be preceded by comparable events in the Southern Dinarides. The above evidence may indicate that a fault in the Southern Apennines cannot easily activate without the contribution of a post-seismic perturbation triggered by one or more major shocks in the Southern Dinarides.

Since the probability that such a correspondence merely occurs by chance is very small [57, 58], it is plausible to suppose that a close tectonic connection exists between the two zones (Figure 6C). The occurrence of a major 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 metres, e.g. [63]), implies a comparable displacement of the adjacent Adria domain, which causes a reduction of vertical flexure in the southern Adriatic domain, as sketched in the section of Figure 6. Such process is expected to induce extensional strain in the Southern Apennines, which may favour the activation of the belt-parallel normal faults recognised in that zone, as for instance the one that generated the 1980 strong earthquake in the Irpinia zone e.g., [35, 64]. 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 [57–60]. Moreover, 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, 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., [52–54, 60, 65–69].

The fact that the above significant correlation can be recognised for the most recent, complete and reliable part of the seismic catalogue may imply that this phenomenon can represent a tool for recognising the periods when the probability of strong shocks in Southern Apennines is undergoing a significant increase. In this view, the fact that since 1979 no earthquakes with $M \geq 6.5$ have occurred in the Southern Dinarides (**Figure 6**) could imply that at present the probability of major shocks in the Southern Apennines is relatively low. Some doubts about this prediction may be raised by the fact that a significant shock recently occurred in the Southern Dinarides (2019, $M = 6.2$). The previous seismic histories would suggest that such event is slightly weak for triggering significant seismicity in the Southern Apennines. However, possible uncertainties in the estimated magnitude could reflect on the reliability of the above prediction.

5. Present seismic hazard in Calabria

The analysis of the seismic histories of Calabria and the Hellenides sector lying between the Ionian islands and Albania, along with the geodynamic context in the central Mediterranean area, suggests a possible connection between these two zones [58, 59, 61]. This interpretation is consistent with the structural/tectonic setting sketched in the section of **Figure 7**, which implies that a seismic slip at the Hellenic thrust zone reduces the upward vertical flexure of the Adriatic lithosphere, so attenuating the resistance that the Calabrian wedge encounters in overthrusting such lithosphere. Since, this last process underlies the main genetic mechanism of Calabrian shocks, one can realise why an earthquake in the Hellenides may cause an increase of seismic hazard in Calabria.

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 [58, 59, 61], which provides insights into the most probable delay between the presumed precursor and the induced event.

The possibility that the above phenomenon was systematic is supported by the comparison of the seismic histories of the two zones involved (**Table 1**), which indicates that all Calabrian seismic crises with $M \geq 6.0$ have been preceded, within

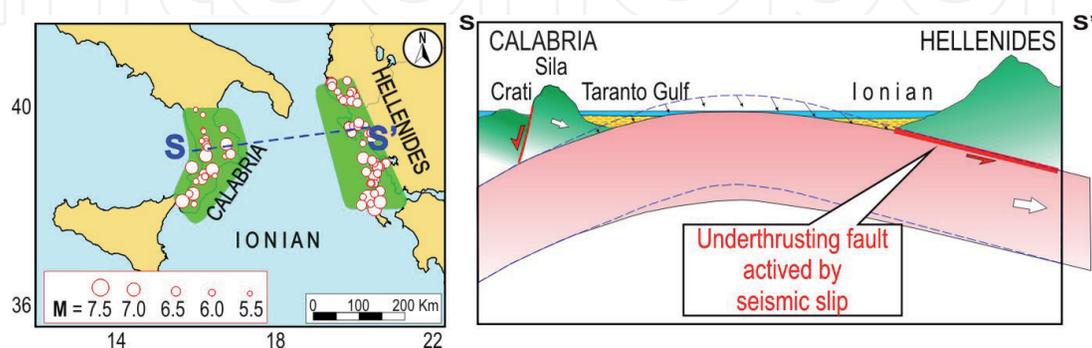


Figure 7. Geometry of the presumably interrelated Calabrian and Hellenic seismic zones and trace of the section (S-S') are shown in the map. Red circles indicate the epicentres of the earthquakes that have occurred in the two zones since 1600 a. D (**Table 1**). The section illustrates a tentative reconstruction (vertically exaggerated) of the reduction of vertical flexure of the Adriatic plate (dashed line) that may occur in response to a strong decoupling earthquake in the Hellenic thrust zone. This effect may favour the outward escape of the uplifted Calabrian wedge towards the Ionian domain. Seismicity data as in **Figure 1**.

Hellenides ($M \geq 6.0$)	Calabria ($M \geq 5.5$)
1601 (6.3)	
1612 (6.3), 1613 (6.3)	
1625 (6.5)	1626 (6.1)
1630 (6.5), 1636 (7.2)	1638 (6.8, 7.1)
1638 (6.3)	1640 (5.8)
1650 (6.2), 1658 (6.7)	1659 (6.6)
1666 (6.2), 1674 (6.3)	
1701 (6.6) , 1704 (6.4)	1708 (5.6)
1709 (6.2), 1714 (6.3)	
1722 (6.3), 1723 (6.1, 6.3), 1732 (6.6)	
1736 (6.0), 1741 (6.3), 1743 (6.9)	1743 (5.9), 1744 (5.7), 1749 (5.8)
1759 (6.3), 1766 (6.6), 1767 (6.7)	1767 (5.9)
1769 (6.8) , 1772 (6.1)	
1773 (6.5)	1783 (7.1, 6.7, 7.0)
1783 (6.5, 6.6), 1786 (6.5)	1791 (6.1)
1809 (6.1), 1815 (6.3), 1820 (6.6)	
1823 (6.3), 1825 (6.7)	1832 (6.7)
1833 (6.5)	1835 (5.9), 1836 (6.2)
1851 (6.8)	1854 (6.3)
1854 (6.0), 1858 (6.0, 6.2, 6.4), 1859 (6.0, 6.2)	
1860 (6.4), 1862 (6.4, 6.2), 1865 (6.3), 1866 (6.6) , 6.2, 6.1, 6.4), 1867 (7.2), 1869 (6.0, 6.7)	1870 (6.2)
1872 (6.0)	
1885 (6.0)	1886 (5.6), 1887 (5.6)
1893 (6.6)	1894 (6.1)
1895 (6.2, 6.5, 6.2, 6.2), 1897 (6.6) , 1912 (6.1)	1905 (7.0), 1907 (6.0), 1908 (7.1) , 1909 (5.5), 1913 (5.6)
1914 (6.0), 1915 (6.1, 6.3, 6.0),	
1920 (6.0, 6.5)	1928 (5.9)
1930 (6.2)	
	1947 (5.7)
1948 (6.5, 6.5)	
1953 (6.0, 6.6, 7.0, 6.2)	
1983 (6.7, 6.0)	
2003 (6.2)	
2014 (6.1, 6.1), 2015 (6.5)	

Table 1.

List of major Hellenic and Calabrian events, occurred since 1600 a.D. in the zones depicted in **Figure 7** (the shocks with $M \geq 6.0$ in Calabria and $M \geq 6.5$ in Hellenides are in **bold**). Seismicity data as in **Figure 1**.

10 years, by at least one event with $M \geq 6.5$ in the Hellenides. Even if lower magnitudes ($M \geq 5.5$) are considered, the correspondence remains fairly significant, since only 3 (out of 29) Calabrian events have not been preceded by equivalent shocks in the Hellenides. The above evidence could imply that a major earthquake can hardly occur in Calabria without being preceded by significant seismic activity in the Hellenides [58, 59].

On the other hand, considering the opposite aspect of the presumed interrelation, one can note that only 11, out of 22, Hellenic seismic crises with $M \geq 6.5$ 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 is affected by significant uncertainty. This problem mainly concerns the most recent time, given that since 1948 no Hellenic events with $M \geq 6.5$ have been followed by an event in Calabria with $M \geq 5.5$ (**Table 1**). Such long quiescence (73 years) is rather anomalous with respect to the previous behaviour, in particular with the fact that from 1626 to 1947 the average inter-event time between $M \geq 5.5$ Calabrian shocks was about 16 years and was never longer than 41 years.

In order to find a possible explanation of the present long quiescence and of the fact that since the middle of the XX century the correspondence between Hellenic and Calabrian earthquakes has undergone a considerable worsening, we advance the hypothesis that such anomalous behaviour is an effect of the considerable increase of E-W compressional stress that developed in the Hellenic and Ionian zones in response to the large westward displacement of the Anatolian-Aegean system since 1939, when a very strong earthquake in Eastern Anatolia ($M = 8$) triggered the progressive activation of the entire North Anatolian fault system (NAF in **Figure 8**, e.g., [71]).

The peculiarity of the above seismic sequence in the NAF is the fact that it also involved the activation of the central NAF, which had been almost silent for a long time e.g., [72]. This rare event favoured a significant westward displacement (some metres) of the whole Anatolian wedge, causing a considerable increase of E-W compression in the zones stressed by the convergence of this block with the Africa-Adriatic domain (**Figure 8**). The least action principle suggests that the fast shortening required by such dynamics was mainly accommodated by the outward extrusion of the Peloponnesus and the central Aegean zones, i.e. the orogenic

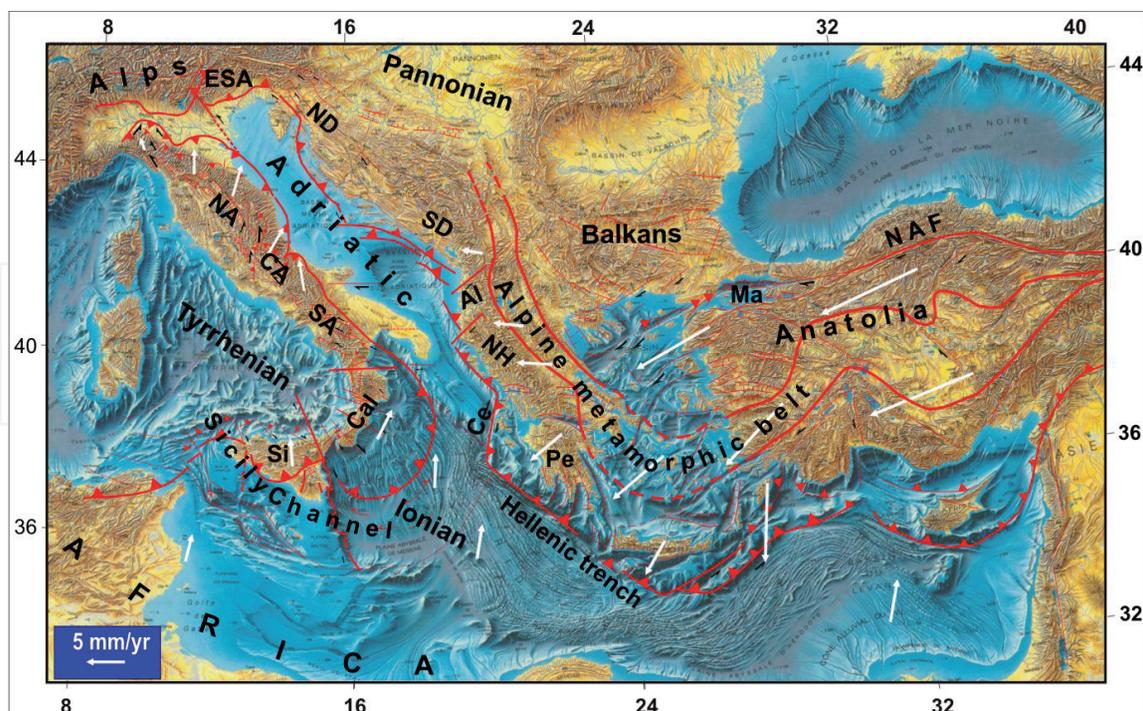


Figure 8. Proposed plate/microplate configuration and kinematic pattern in the Central Mediterranean and Aegean-Anatolian region [14]. White arrows indicate the presumed velocity field with respect to Eurasia. Land and seafloor morphological features from Le Pichon and Biju-Duval [70]. Thick red lines delimitate for reference the inner part of the Alpine metamorphic belt. Al = Albanides; CA, NA, SA = Central, Northern and Southern Apennines, Cal = Calabrian Arc, Ce = Cephalonia fault system, ESA = Eastern Southern Alps, Ma = Marmara, NAF = North Anatolian fault system, ND = Northern Dinarides, NH = Northern Hellenides, Pe = Peloponnesus, SD = Southern Dinarides, Si = Sicily. Symbols as in **Figure 2**.

structures which were facing the thin and dense (low buoyancy) Ionian oceanic lithosphere e.g., [73]. The extrusion of the northern Hellenides (facing the thicker and more buoyant Adriatic continental domain) would have instead encountered much higher resistance. This hypothesis may explain why since about 1947 (when the effects of such strong perturbation might have reached the western Hellenic zone) most seismic activity has occurred in the Aegean zones lying south of the Cephalonia fault system and the North Aegean trough, while minor activity has instead occurred in the Northern Hellenides (**Figure 9**).

Since the activation of that Hellenic thrust zone is supposed to be a necessary condition for the occurrence of Calabrian earthquakes (**Figure 7** and **Table 1**), the above evidence could explain why since 1947 no major events have occurred in Calabria. The same interpretation may help to understand why in the 1850–1908 time interval, characterised by very high seismic activity in the Hellenides sector, very strong earthquakes occurred in Calabria (**Table 1**).

The evidence and arguments described above suggest that the probability of strong earthquakes in Calabria will not undergo a significant increase until the

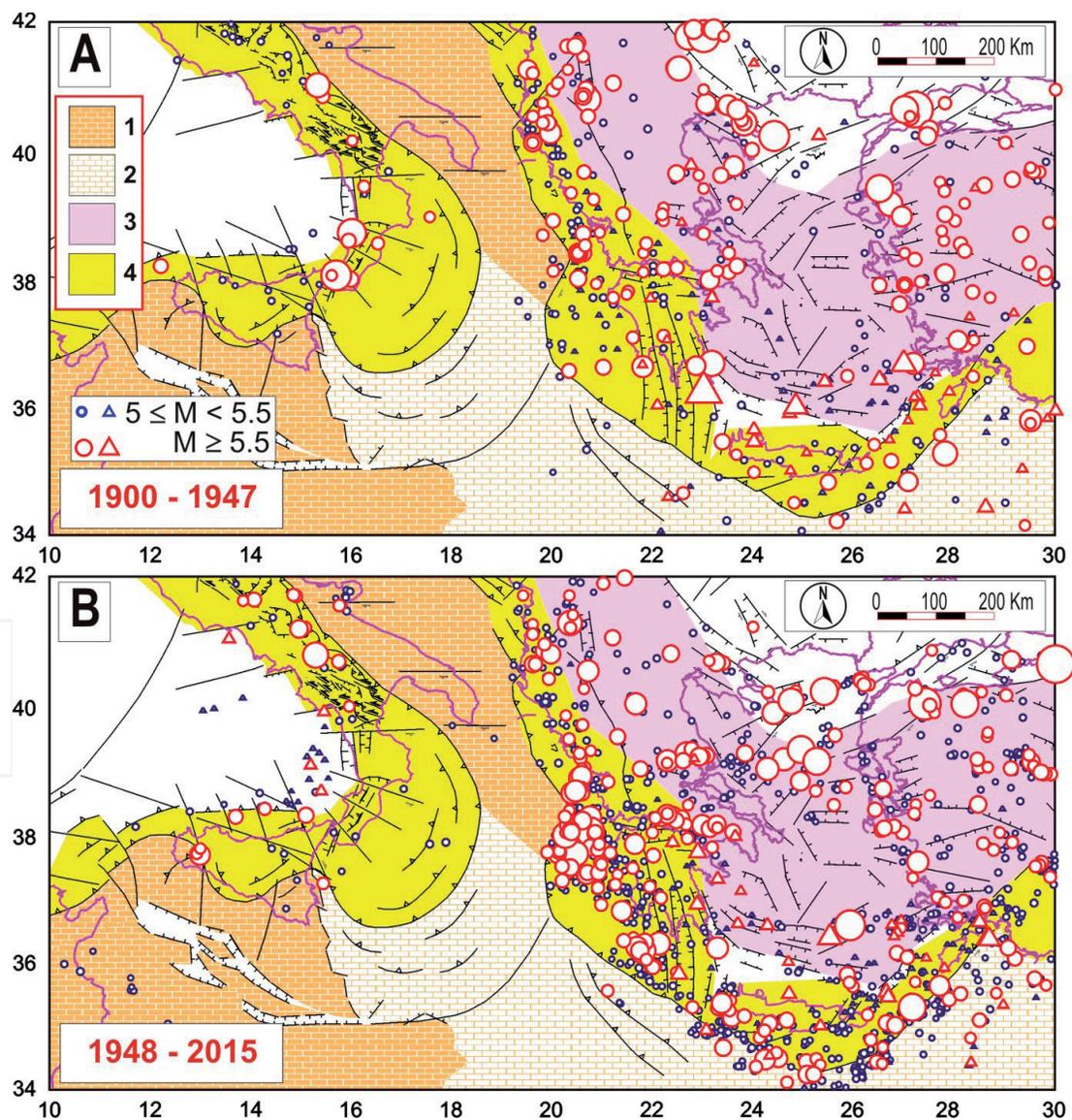


Figure 9. Distribution of major earthquakes occurred in two time intervals (A and B) which respectively preceded and followed the presumed arrival in the Aegean area of the effects of the large westward displacement of the Anatolian wedge, triggered by the strong 1939 earthquake ($M = 8$) in the easternmost north Anatolian fault system [74, 75]. 1) Africa-Adriatic domain 2) oceanic Ionian domain 3) Alpine metamorphic belt 4) orogenic belts. Circles and triangles respectively indicate focal depths lower and greater than 60 km. Seismicity data as in **Figure 1**.

occurrence of major shocks in the Hellenides thrust zone. The fact that three earthquakes with $M > 6$ recently occurred in the Cephalonia zone (2014 and 2015) cannot easily be taken as a possible precursor of Calabrian shocks, since in the tectonic context created by the Anatolian westward displacement other very strong events (1953, $M = 7.0$, 6.6; 1983 $M = 6.7$) affected the Cephalonia fault without inducing significant seismic activity in Calabria.

6. Conclusions

It is advanced the hypothesis that the spatio-temporal distribution of major earthquakes in the periAdriatic zones (**Figure 4**) is closely connected with the progressive roughly northward displacement of the Adria plate. This motion is allowed by the seismic activations of the decoupling fault systems located along the lateral boundaries of Adria (Dinarides and Apennines) and the Eastern Southern Alps. This migrating pattern of earthquakes may tentatively be recognised in the period considered (1300–2020), delineating 7 already developed sequences and one partially developed migration. Taking into account the regularities that we tentatively recognise in the first 7 seismic sequences and the main features of the last ongoing one (which has already involved intense seismic crises in the Southern and Central Apennines and in the western boundary of the RMU wedge in the Northern Apennines) we suppose that the boundaries of the northern RMU wedge (Rimini-Ancona thrust, Romagna fault and Alta Valtiberina trough), along with the Emilia Apennines (stressed by the RMU wedge, **Figure 2**) are the zones most prone to the next strong earthquakes in the Apennine belt.

Further insights into the present seismic hazard in two major Italian seismic zones (Southern Apennines and Calabria) are tentatively inferred from the presumed tectonic connection of such regions with other periAdriatic zones. The first tectonic connection (suggested by seismic histories of about two centuries, **Figure 6**) provides that a strong earthquake ($M \geq 6.0$) in the Southern Apennines cannot easily occur if not preceded (within 5 years) by a shock with $M \geq 6.5$ or by more than one shock with $M \geq 6.0$ in the Southern Dinarides. Even if weaker shocks are taken into account, the correlation remain significant, since almost all Southern Apennines shocks with $M \geq 5.5$ (14 out of 15) have been preceded by seismic phases in the Southern Dinarides involving more than one shock (2–5) with $M > 5.5$.

Assuming that the presumed implications of the above correspondence can be taken as realistic for the next years, one could try to estimate the present seismic hazard in the Southern Apennines. To this purpose, one have to take into account the recent seismic activity in the Southern Dinarides, which only includes an event with $M = 6.2$ in 2019 (Albania). The fact that the magnitude of such shock was lower than 6.5 would imply a low probability for the occurrence of a Southern Apennine shock with $M \geq 6$, while the occurrence of a weaker shock cannot easily be excluded.

The possible tectonic connection between Calabrian and Hellenic earthquakes (**Figure 7** and **Table 1**) is suggested by the seismic histories of these two zones for the period 1600–1947. However, in the subsequent time, this correspondence cannot be recognised, mainly due to the fact that no more earthquakes with $M \geq 5.5$ have occurred in Calabria. We suggest that such quiescence is an effect of the considerable westward displacement that the whole Anatolian wedge has undergone due to the activation of the full NAF fault system. That event has caused a noticeable increase of E-W compression in the Ionian and Calabrian zones, so enhancing the

resistance against the outward escape of the Calabria wedge. Since this process is the main genetic mechanism of seismicity in Calabria, the above effect can help to explain the recent seismic quiescence in that zone (**Table 1**). If this interpretation is realistic, one could suppose that in the present context seismic hazard in Calabria is not high, since in recent times no major earthquakes have occurred in the Hellenides sector lying north of the Cephalonia zone, i.e. the area that generated the main precursors of the strongest Calabria earthquakes. Recent seismicity only affected the Cephalonia fault system (2014, $M = 6.1$, 6.1 and 2015, $M = 6.5$), that in the ongoing stress regime have already involved other major shocks with no effects in Calabria.

The above considerations about the present seismic hazard in the Southern Apennines and Calabria reinforce our conviction that the Northern Apennine zones cited above should be taken as priority zones in a prevention plan in Italy.

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