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Short-Term Kinematics of the Adria Plate and Space-Time Distribution of Major Peri-Adriatic Earthquakes

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Abstract

Seismic activity is quite strong in the peri-Adriatic zones, whereas the internal part of the Adria plate is almost aseismic. This pattern suggests that Adria is a solid block that interacts with the surrounding belts, trying to move roughly northward. Each major earthquake in a peri-Adriatic zone triggers the acceleration of the decoupled Adria sector, which induces a perturbation of the stress/strain fields in the still blocked boundaries of the plate. Step by step, the displacement of Adria involves more and more northern zones to finally reach the northern front of the plate (eastern Southern Alps). This interpretation seems to be compatible with the time patterns of seismic activity in the main peri-Adriatic zones since 1600 A.D., which may suggest repeated northward migrations of seismic crises. Each supposed migrating sequence involves major earthquakes in most zones. The main features of the first 4 seismic sequences (1600-1930) are used to get insights into possible regularities in the progressive activations of the peri-Adriatic zones. This information and the main features of the ongoing migrating sequence (since 1931) are then used to tentatively recognize the peri-Adriatic zones where the occurrence of next major earthquakes may be most likely.

Keywords

Tectonics, Adriatic, Short-Term Plate Kinematics, Seismicity Distribution

1. Introduction

The Adriatic domain was a promontory of Nubia until the Late Miocene (**Figure 1(a)**), when this domain, stressed by the westward push of the Anatolian-Aegean-Pelagonian belt, decoupled from Nubia, becoming an independent microplate [1] [2] [3] [4] [5]. This decoupling was allowed by the activation of a major discontinuity running through the Ionian and Pelagian domains (Victor Hensen-Medina and Sicily Channel fault systems, **Figure 1(b)**). Once decoupled, the Adria plate underwent a clockwise rotation accompanied by a minor NNW ward motion until the late Pliocene [1] [2] [3] [4] [5].

As during the Pliocene most thinned peri-Adriatic domains were consumed, the mobility of Adria underwent a considerable reduction in the Early Pleistocene (**Figure 1(c)**). Since then, the westward push of the Anatolian-Aegean-Pelagonian belt has been mainly accommodated by the E-W shortening of the southern Adria domain, mainly through upward flexure and crustal thickening (**Figure 2**).

Since the middle Pleistocene (**Figure 1(d)**), the Adriatic plate has recovered some mobility, due to the combined effects of the Nubia-Eurasia convergence and of the release of the southern Adria gravity potential accumulated during the previous shortening phase. This plate motion is suggested by the deformation patterns observed in the surrounding belts ([2] and references therein, [11]-[17]). In the Hellenides, Albanides, Dinarides and eastern Southern Alps compressional tectonics dominated. In the Apennines the deformation pattern was more complex, due to the peculiar interaction of Adria with that belt that was mainly characterized by different belt-parallel shortenings in the eastern and western sectors (**Figure 3**). This difference was determined by the fact that the eastern side of the belt, being more connected with the underlying Adria domain, was stressed northward more efficiently than the western side, which was less connected with the (deeper) buried Adriatic margin (e.g., [1] [2] [3] [5] [7] [18]). Since the northernmost Apennine belt (Ligurian units) was almost fixed, due to the lack of a yielding, evaporitic layer at the bottom of the sedimentary cover (e.g., [19] [20] [21] [22]), the stress of Adria caused significant belt-parallel shortening in the outer chain, accommodated by uplift, outward extrusion of wedges (Molise-Sannio = MS, and Romagna-Marche-Umbria = RMU) and activation of some transversal thrust fronts (Olevano-Antrodoco-Sibillini and Sangro-Volturno), as shown in **Figure 3**. Compressional and extensional/transtensional deformations respectively developed along the outer and inner sides of the MS and RMU extruding wedges (**Figure 3**). The Matese, Benevento, Irpinia extensional features developed in the wake of the MS wedge and the Norcia-Colfiorito, Gualdo Tadino, Alta Valtiberina, and Valle Umbra troughs formed in the wake of the RMU wedge. In the Central Apennines (Latium-Abruzzi platform) the decoupling between the outer and inner parts of the belt has been allowed by two main transtensional faults (L'Aquila and Fucino).

In the long-term (geological), the Adriatic plate is moving in almost close connection with Nubia. In the short-term, the kinematics of that plate is not continuous. The motion of the surrounding plates (Nubia, Eurasia and Anatolian-Aegean system) causes a deformation of Adria inducing an increase of stress along the surrounding fault systems. When friction is overcome in one fault, an

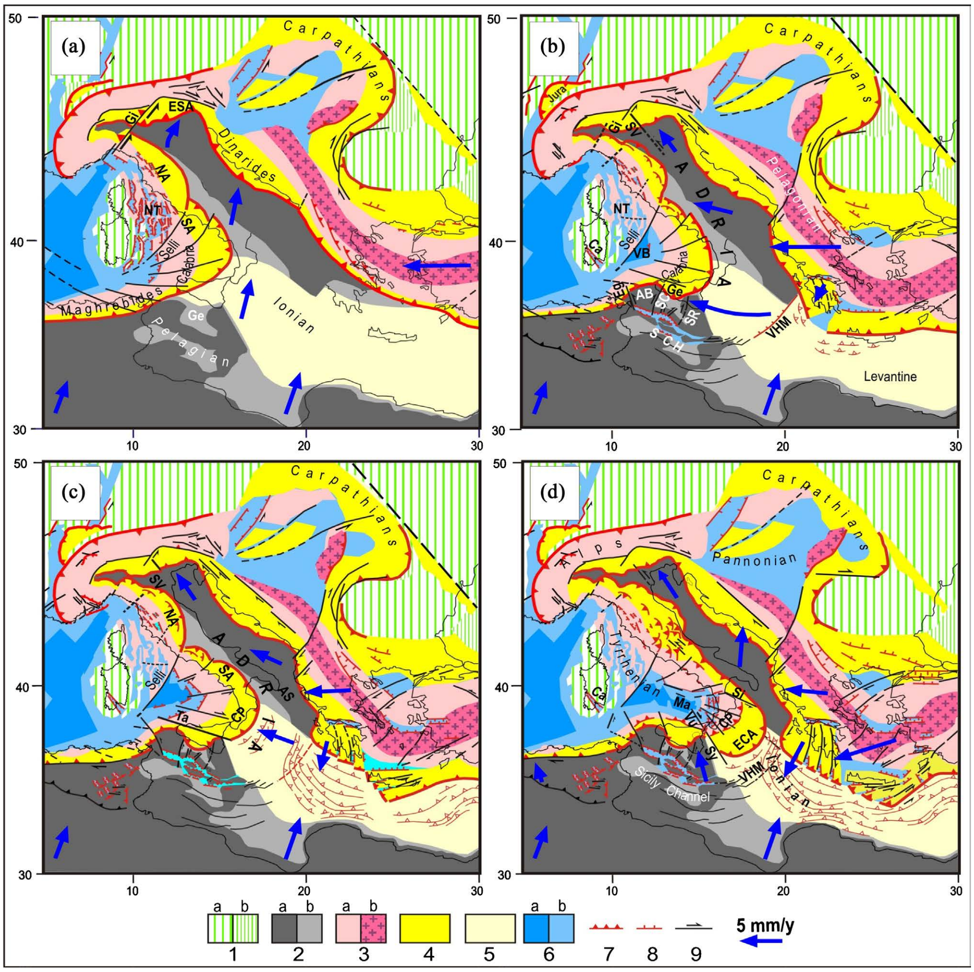

Figure 1. Proposed tectonic-kinematic evolution of the central Mediterranean region since the Miocene (e.g., [3] [5]). 1) Continental (a) and thinned continental (b) Eurasian domains; 2) Continental (a) and thinned continental (b) Nubia/Adriatic domains; 3) Anatolian-Aegean-Pelagonian belt, constituted by ophiolitic units (a) and crystalline massifs (b) 4) Other orogenic belts; 5) Ionian Tethys oceanic domains 6) Zones affected by intense (a) or moderate (b) crustal thinning; 7, 8, 9) Compressional, tensional and strike-slip features. Blue arrows indicate the proposed kinematic pattern [2]-[7]. Present geographical contours (thin black lines) are reported for reference. (a) Late Miocene. The reactivation of the Giudicarie fault system (Gi) allowed the main Adriatic domain to move roughly NE ward with respect to its northwestern edge. The consequent divergence between the main Adriatic domain and the fixed Corsica-Sardinia block induced crustal extension in the interposed sector of the Alpine-Apennine belt, forming the Northern Tyrrhenian basin (NT). ESA = Eastern Southern Alps; NA = Northern Apennines; SA = Southern Apennines; (b) Early Pliocene. The westward push of the Anatolian-Aegean-Pelagonian system causes the decoupling of the Adria plate from Nubia by the activation of the Victor Hensen-Medina-Sicily Channel fault system. Once decoupled, Adria underwent a clockwise rotation and a minor NW ward motion. The NW displacement caused the activation of the Schio-Vicenza fault system in the northern Adriatic domain. AB = Adventure block, Ca = Campidano graben, Eg = Egadi fault, Ge = Gela nappe, SCH = Sicily Channel, SC = Sciacca fault, SR = Scicli-Ragusa fault, SV = Schio-Vicenza fault, VB = Vavilov basin, VHM = Victor Hensen-Medina fault. (c) Late Pliocene-Early Pleistocene. Since the suture of the Southern Apennine consuming boundary the lateral escape of the Alpine-Apennine material has only involved the Calabria-Peloritani (CP) wedge, which has extruded roughly SE ward at the expense of the Ionian oceanic domain. Stressed by E-W compression, the southern Adriatic plate has undergone upward flexure, accelerating the formation of the Apulian Swell (AS). In this strong compressional context, the CP wedge has undergone fast uplift, bowing and fragmentation. (d) Pleistocene. The Nubia-Eurasia convergence along with the potential gravitational energy accumulated by the southern Adriatic in the previous phase triggered the northward displacement of Adria. Accretionary activity along the outer Calabrian front formed the External Calabrian Arc (ECA), while crustal extension developed in the wake of the migrating arc, forming the Marsili basin (Ma). Since the collision of the extruding CP wedge with the Adriatic continental domain, the escape trend of such wedge changed by activating new lateral guides, the Sibari (Si) and Vulcano-Syracuse (Vu-Sy) fault system.

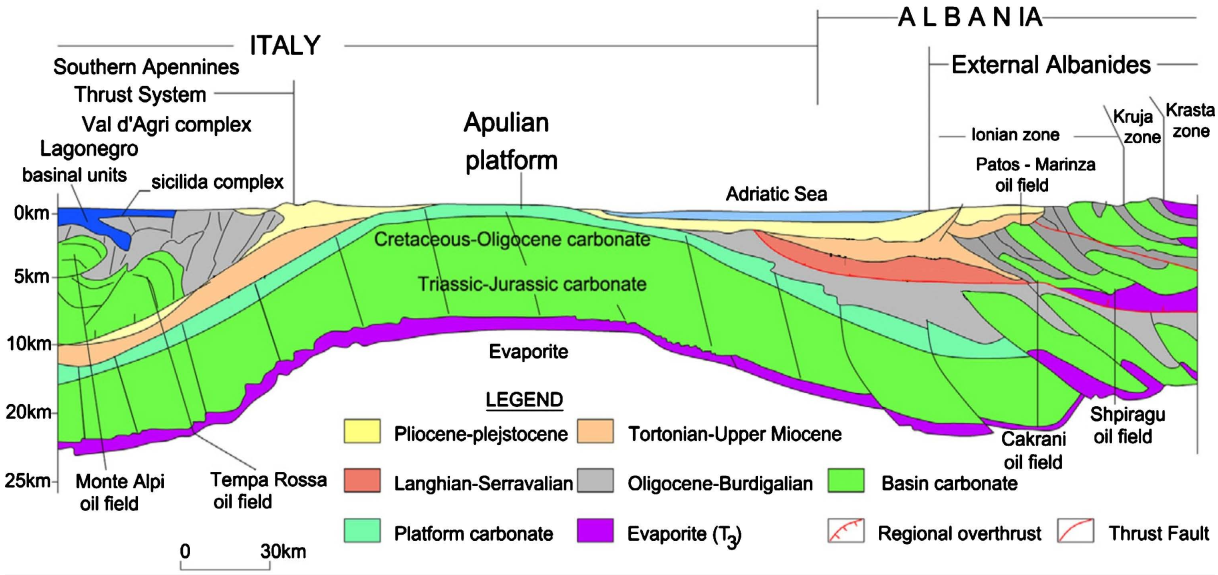

Figure 2. Section across the southern Adriatic domain (From [8], modified). The upward flexure of this domain testifies a strong E-W compression, driven by the convergence between the Anatolian-Aegean-Pelagonian belt and Nubia [4] [5] [6] [9] [10].

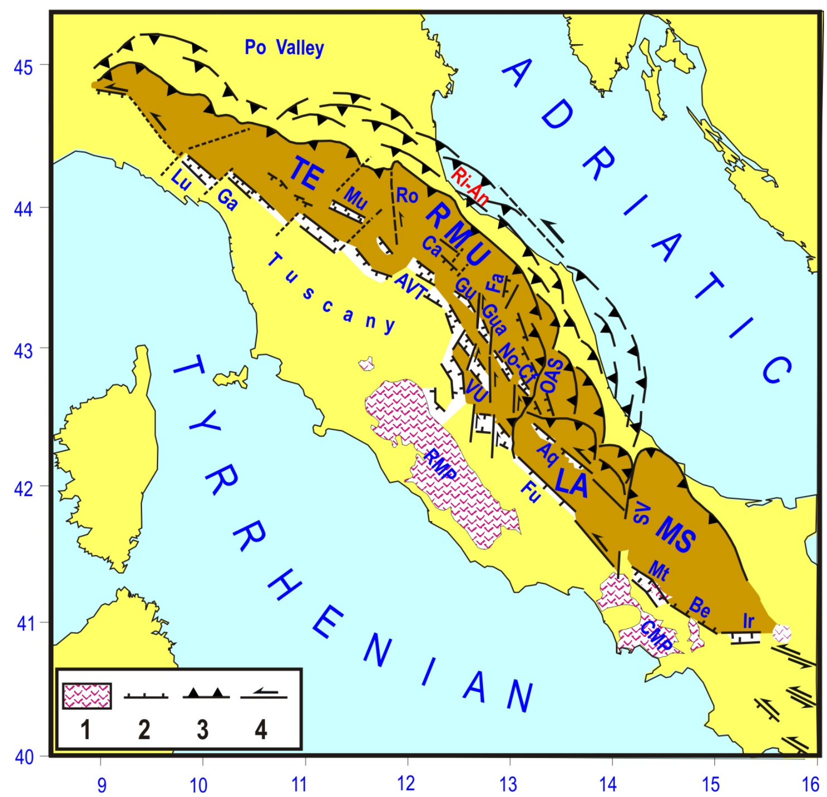

Figure 3. Tectonic setting in the Apennine belt. 1) Main Quaternary volcanic areas; 2, 3, 4) Tensional, compressional, and strike-slip features. The brown zone evidences the portion of the belt that is stressed by the Adria plate. Aq = L'Aquila fault, AVT = Alta Valtiberina trough, Be = Benevento fault, Ca = Cagli fault, CMP = Campanian magmatic province, Fa = Fabriano fault, Fu = Fucino fault, Ga = Garfagnana trough, Gua = Gualdo Tadino fault, Gu = Gubbio fault, Ir = Irpinia fault, LA = Latium-Abruzzi platform, Lu = Lunigiana trough, MS = Molise-Sannio wedge, Mt = Matese fault, Mu = Mugello trough, No-Cf = Norcia-Colfiorito fault, OAS = Olevano-Antrodoco-Sibillini thrust front, Ri-An = Rimini-Ancona thrust front, RMP = Roman magmatic province, RMU Romagna-Marche-Umbria wedge, Ro = Romagna Apennines fault, SV = Sangro-Volturno thrust front, TE = Tuscany-Emilia wedge, VU = Valle Umbra fault.

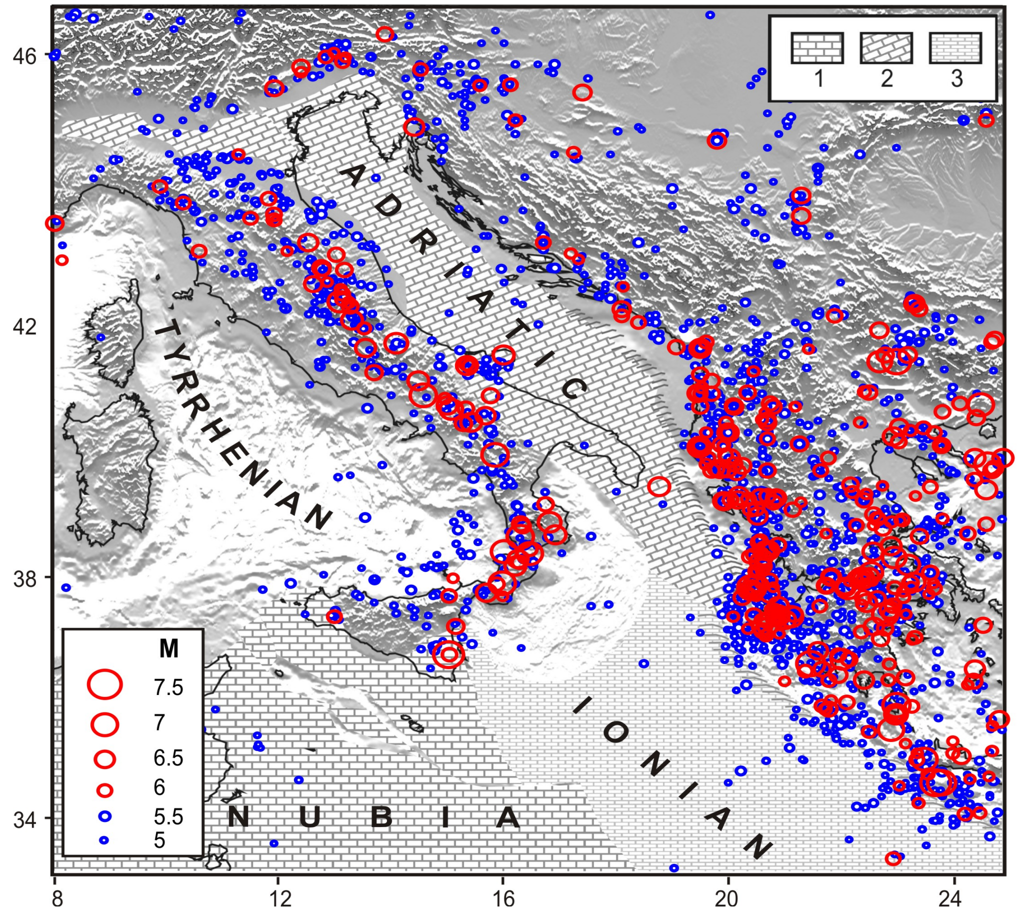

Figure 4. Major earthquakes occurred in the central Mediterranean region since 1600 A.D. 1, 2) Nubia and Adriatic continental domains 3) Ionian oceanic domain. Data from [25]-[32].

earthquake occurs and the decoupled Adriatic sector undergoes acceleration, producing a stress perturbation that gradually propagates through the plate, with velocities controlled by rheological properties. As this process develops, further decoupling earthquakes involve other peri-Adriatic fault systems, up to reach the northern Alpine front (e.g., [2] [23] [24]). This work describes our attempt to check the reliability of the above interpretation by analyzing the seismic histories of the main peri-Adriatic zones.

2. Short-Term Adria Kinematics and Seismicity Distribution

To recognize eventual regularities in the distribution of peri-Adriatic earthquakes we have taken into account the time patterns of seismic activity in the various sectors of the peri-Adriatic boundaries since 1600 A.D. The choice of the sectors to be used in this analysis is based on a detailed reconstruction of the tectonic setting in the study area (**Figure 5**), also involving the buried margins of the Adria plate (**Figure 6**).

The seismic activation of the dextral transpressional Cephalonia fault allows the southernmost part of Adria to decouple from the southward escaping Peloponnesus wedge (**Figure 5**). Major earthquakes in the Hellenides (Epirus), Albanides

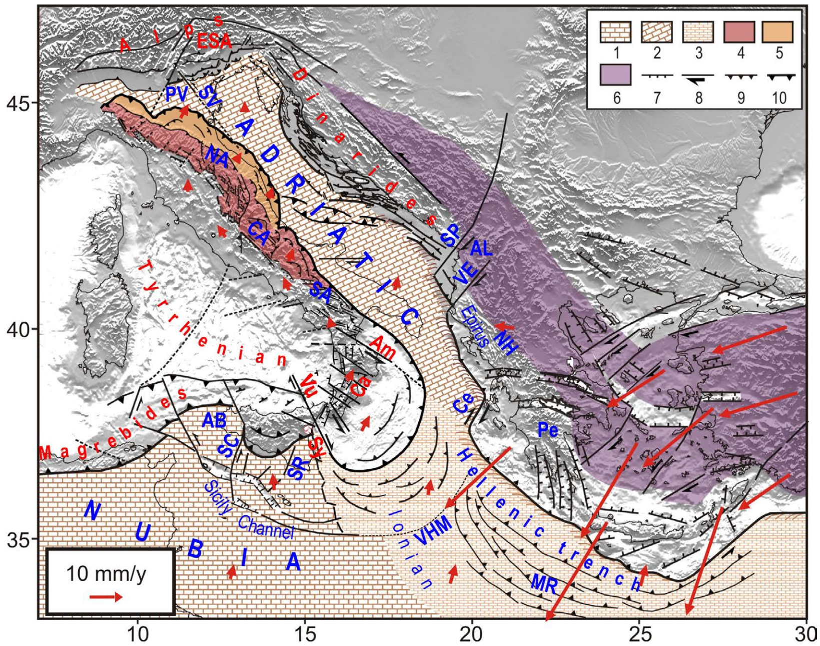

Figure 5. Present tectonic and kinematic settings of the central Mediterranean area. Stressed by the Adriatic plate, the eastern part of the Apennine belt (brown) is undergoing belt-parallel shortening, accommodated by uplift and formation of arcs. 1-2) Nubia and Adriatic continental domains 3) Ionian domain 4) Outer mobile side of the Apennine belt 5) Buried external folds in the Northern Apennines 6) Anatolian-Aegean-Pelagonian belt 7, 8, 9) Tensional, transcurrent and compressional features 10) Outer thrust fronts. Al = Albanides; AB = Adventure block, Am = Amendolara fault, Ca = Calabrian wedge, Ce = Cephalonia fault, ESA = Eastern Southern Alps, MR = Mediterranean ridge, NA, CA, SA = Northern, Central and Southern Apennines, NH = Northern Hellenides, Pe = Peloponnesus; PV = Po Valley; SC = Sciacca fault; SP = Scutari-Pec fault, SR = Scicli-Ragusa fault; SV = Schio-Vicenza fault, VE = Vlora-Elbasan fault; VHM = Victor Hensen-Medina fault system; Vu-Sy = Vulcano-Syracuse fault system. Red arrows indicate the present kinematic field [4] [6] [33] [34].

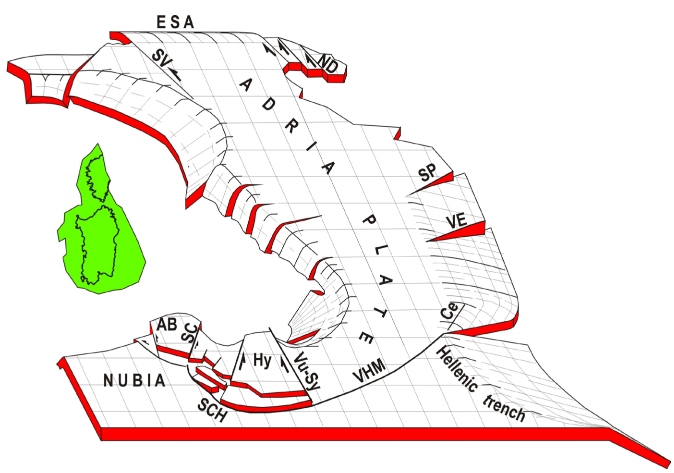

Figure 6. Perspective view of the Adria plate and its buried margins. The shallow structures are shown in Figure 5. AB = Adventure block, Ce = Cephalonia fault, ESA = Eastern Southern Alps, Hy = Hyblean plateau, ND = Northern Dinarides, SC = Sciacca fault, SCH = Sicily Channel fault system, SP = Scutari-Pec fault, SV = Schio-Vicenza fault, VE = Vlora-Elbasan fault, VHM = Victor Hensen-Medina fault system, Vu-Sy = Vulcano-Syracuse fault system.

and Southern Dinarides allow the Adria plate to underthrust such belts, to accommodate the E-W shortening driven by the convergence of the Adria plate with the Anatolian-Aegean-Pelagonian system. Furthermore, a dextral transpressional decoupling is recognized in the Albanides in some transversal faults, such as the Scutari-Pec and Vlora-Elbasan ones (**Figure 6**).

The above-mentioned stress regimes are suggested by geological evidence and earthquake focal mechanisms (e.g., [17] [35] [36]). The acceleration of southern Adria also requires decoupling of this plate from the Calabrian wedge, that is forced to overthrust the Ionian slab, belonging to Adria (**Figure 5** and **Figure 6**, e.g., [2] [3] [5]). Along the western boundary of Adria decoupling earthquakes may occur in the axial parts of the Apennine belt (**Figure 3**). In these zones**,** seismicity allows the outer belt to decouple from the inner belt. In the southern Apennines major extensional shocks in the Matese, Benevento and Irpinia fault zones are induced by the divergence between the extruding MS wedge and the inner side of the belt. In the central Apennines (Latium-Abruzzi platform) major earthquakes mainly occur along two major sinistral transtensional faults (L'Aquila and Fucino), whose activations allow the eastern belt to move roughly NW ward with respect to the almost fixed western belt. In the northern Apennines, the decoupling between the outer and the inner belts develops along a series of belt-parallel extensional faults (Norcia, Colfiorito, Valle Umbra, Gualdo Tadino, Gubbio, Alta Valtiberina). Seismicity also occurs along the compressional boundary of the RMU wedge (Rimini-Ancona thrust front) and along a major transversal fault (Romagna) that allows the decoupling of the RMU wedge from the Tuscany-Emilia Apennines. The role of this last discontinuity is mainly revealed by the occurrence of major shocks (e.g., [23] [24] [37] [38]). The decoupling of Adria with respect to the Northern Dinarides is allowed by SE-NW transpressional fault systems (**Figure 5**, e.g., [17] [39] [40])). In the eastern Southern Alps, the Adria plate underthrusts this chain (e.g., [39] [41]). The border between the main Adria domain and its Po Valley sector is marked by the Schio-Vicenza fault zone, which however is not affected by frequent and strong seismicity (**Figure 5**). The peri-Adriatic zones taken into account in the following analysis are shown in **Figure 7**.

The first zone in **Figure 7** corresponds to the collisional boundary between Adria and the Aegean-Pelagonian system, including the Cephalonia fault, the northern Hellenides (Epirus), the Albanides and the southern Dinarides thrust fronts (**Figure 5**). The second zone includes the Calabrian wedge. Main earthquakes in this wedge occur at the numerous fault systems generated by the convergence of the confining plates [2] [3] [5] [10]. The third and fourth zones relate to the southern and central sectors of the Apennine belt respectively (**Figure 3**). In the southern Apennines the major decoupling tensional faults are the Irpinia, Benevento and Matese. In the central Apennines there are two major belt-parallel faults (L'Aquila and Fucino), that alternatively allow the decoupling of the outer mobile sector of the belt from the inner one. The fifth zone corresponds to the inner (western) boundary of the Romagna-Marche-Umbria (RMU)

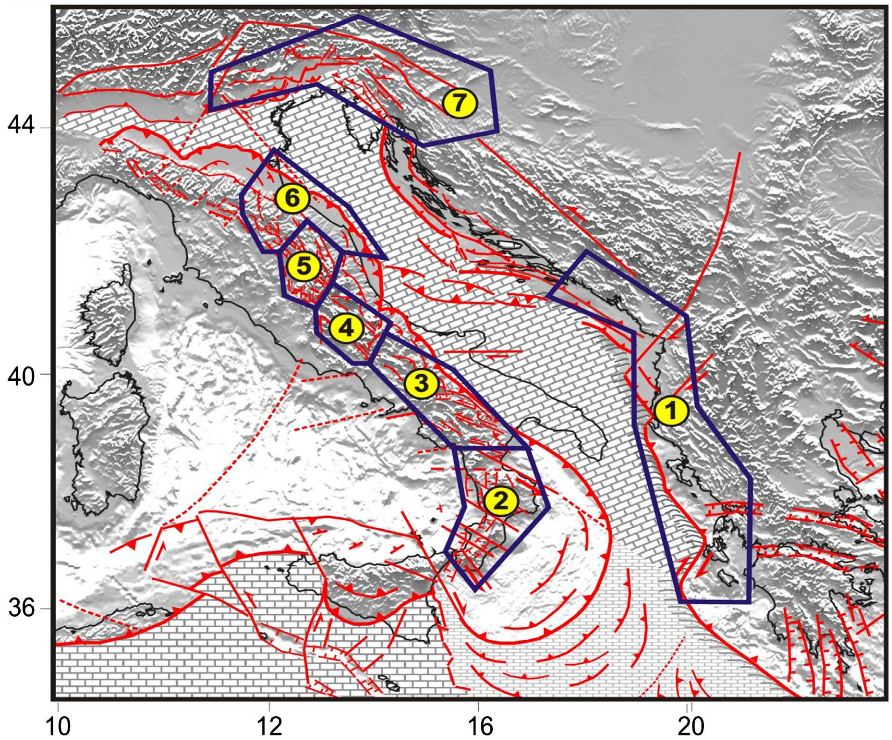

Figure 7. Geometries of the peri-Adriatic boundary zones used for studying the time patterns of seismicity (Figure 8 and Figure 14). 1) Hellenides-Albanides-Southern Dinarides, 2) Calabria, 3) Southern Apennines, 4) Central Apennines, 5) Southern part of the RMU wedge, 6) Northern part of the RMU wedge, 7) Eastern Southern Alps and Northern Dinarides. Symbols as in Figure 5.

wedge, where major belt-parallel extensional/transtensional faults are located (Norcia-Colfiorito, Valle Umbra, Gualdo Tadino, Gubbio). Main shocks in these faults allow the decoupling between the southern RMU wedge and the inner belt (Tuscany). The sixth zone includes the three main boundaries of the northern RMU wedge (the Alta Valtiberina trough, the Romagna shear fault and the Rimini-Ancona thrust front). Major earthquakes in these zones allow the decoupling of the northern RMU wedge from the inner belt (Tuscany), the Emilian Apennines and the Adria domain, respectively. The seventh zone corresponds to the northern boundaries of the Adria plate, running from the Northern Dinarides (characterized by a series of dextral transpressional faults) to the eastern Southern Alps, where Adria underthrusts this belt. Major earthquakes in this zone allow the last step of the Adria's northward displacement.

The main earthquakes that have occurred since 1600 A.C. in the peri-Adriatic zones here considered are reported in Figure 8.

The southeastern zones (Hellenides, Albanides, Southern Dinarides) show an almost continuous activity, only interrupted in some short phases. The active periods most probably trigger a northward displacement of southern Adria. The fact that every 80 - 100 years a more or less intense seismic crisis occurs in the Northern Dinarides and the eastern Southern Alps may indicate that the accelerations of Adria (started in the southern zones) propagate through the

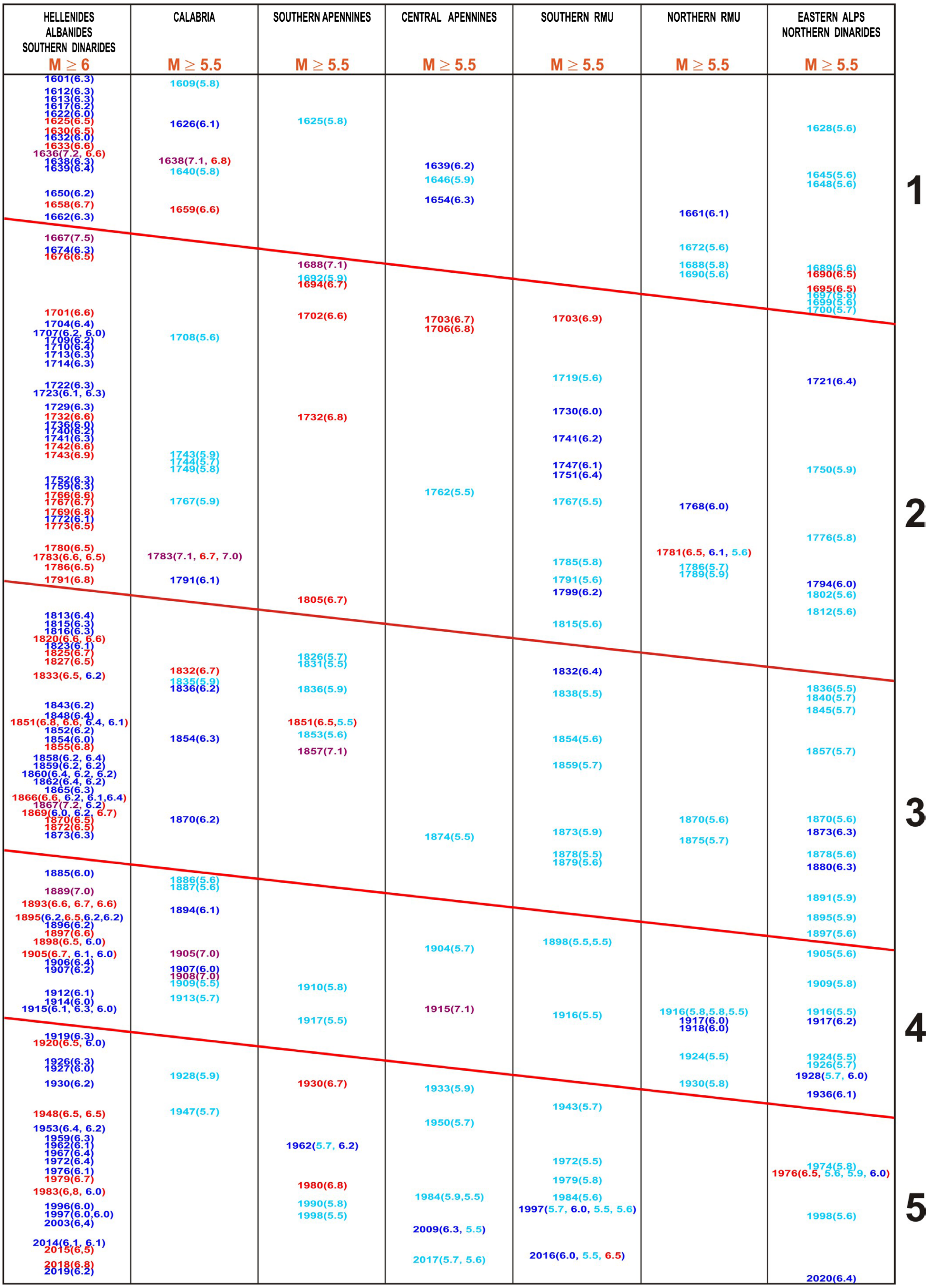

Figure 8. Main earthquakes that occurred in the periAdriatic zones (**Figure 7**) since 1600. Each shock is identified by year and magnitude. Violet symbols for M ≥ 7, red for M ≥ 6.5, blue for M ≥ 6, light blue for M ≥ 5.5. Seismicity data as in **Figure 4**.

plate to reach its northern front, notwithstanding some Apennine zones are not interested by significant seismicity during such phases. The distribution of earthquakes in **Figure 8** seems to support the above interpretation, as seismic crises show a general tendency to migrate from the southern zones to the northern ones. This trend may be recognized in the framework of five migrating seismic sequences, tentatively evidenced by oblique black lines. Each sequence involves significant seismic crises in most zones and low activity in one or two zones. For instance, the central Apennines were affected by strong earthquakes only in 1703-1706 (L'Aquila fault system) and in 1915 (Fucino fault system). These two major crises are separated by a long period (more than 210 years) of low seismic activity (during which only three events of magnitude between 5.5 and 5.8 have occurred). This implies that the central Apennines can be affected by stress increase, induced by a migrating sequence, without undergoing major ruptures. This might be due to the fact that the Latium-Abruzzi carbonate platform (central Apennines) is characterized by higher rigidity with respect to the orogenic material that forms the MS and RMU wedges in the southern and northern Apennines (**Figure 3**).

Some considerations can be made about the main features of the proposed 5 sequences (**Figure 8**) and their possible connection with the tectonic setting in the peri-Adriatic zones.

The first sequence involved strong earthquakes (reaching magnitudes greater than 7) in the southernmost zones (Hellenides, Albanides, southern Dinarides and Calabria). Seismic activity was low or null in the southern Apennines and in the southern RMU wedge, while the central Apennines were affected by some shocks (1639 M = 6.2, 1646 M = 5.9, 1654 M = 6.3). The possibility that such stress propagation migrated through the whole Adriatic domain may explain the occurrence of a significant seismic crisis in the northern peri-Adriatic zones (Northern Dinarides and eastern Southern Alps, **Figure 8**).

The second sequence was triggered by strong earthquakes in the southernmost zones, with particular regard to the very strong 1667 shock (M = 7.5) in the southern Dinarides. The perturbation induced by that event may have caused a sudden stress increase in the Apennine belt, as revealed by the occurrence of strong shocks in the southern Apennines (1688 M = 7.1, 1694, M = 6.7, 1702 M = 6.6) and central Apennines (1703 M = 6.7, 1706 M = 6.8). The long series of shocks that followed in the southern RMU wedge, along the troughs aligned with the L'Aquila fault (1719-1767) could have been triggered by the rupture of the Norcia-Colfiorito fault in 1703 (M = 6.9). The displacement of the central Adria domain caused by these earthquakes may have favoured the occurrence of intense shocks in the northern Adriatic boundaries (1721-1812).

In the third sequence, the main seismic crisis in the eastern Adriatic zones (**Figure 8**) was followed by strong earthquakes in Calabria and the southern Apennines (1832-1857). The quiescence of the central Apennines that characterized most of the previous sequences continued in this sequence. The long seismic silence in this zone may reasonably be interpreted as an effect of the considerable release of stress that occurred at the beginning of XVIII century. The fact that this sequence was characterized by the occurrence of numerous earthquakes in the northern Adriatic zones indicates that notwithstanding the non activation of the central Apennines the displacement of Adria propagated up to the Alps.

In the fourth sequence, seismic activity in the eastern peri-Adriatic zones and Calabria mainly occurred in the period 1893-1908. The perturbation triggered by these strong shocks may have considerably increased stress accumulation in the central Apennines, where a very strong earthquake occurred in 1915 (Fucino, M = 7.1). On its turn, this major rupture may have triggered the stress perturbation that caused the activation of most fault zones in the northern Apennines and the northern Adriatic zones (1916-1936).

After the fourth sequence, a number of relatively strong earthquakes occurred in most zones, but in Calabria and the northern RMU wedge, where seismic activity has been so far very low (**Figure 8**). Some considerations can be made about the possible implications of these two quiescences for the future seismic activity in the study area.

As concerns Calabria, one can note that the time length of the ongoing quiescence for M ≥ 6 earthquakes (114 years after the 1908 shock) is comparable to the one of the previous longest quiescence (1659 − 1783 = 124 years, **Figure 8**). This could indicate a relatively high seismic hazard in that zone. However, in this regard, one should take into account that the lack of major earthquakes (M ≥ 5.5) in Calabria since 1948 may have been significantly influenced by the effects of an exceptional tectonic event, *i.e.* the seismic activation of the entire Anatolian fault since 1939 (e.g., [4] [9] [10] [42] [43] [44]). This major decoupling triggered a large westward displacement (some meters) of the Anatolian-Aegean-Pelagonian system, which led to a considerable increase of E-W compression in the southern Adria and Calabria. The transient time evolution of this displacement and of the consequent stress perturbation in the zones involved developed by velocities compatible with the rheological properties of the structures involved (e.g., [43] [44]). Due to the considerable increase of E-W compression, the friction at the Calabrian faults increased. This effect might explain the cessation of seismic activity in Calabria after 1947 (a time that roughly corresponds to when the major effects of such stress perturbation may have reached the Calabrian zones). Since estimating how long this mechanism can prevent rupturing of the Calabrian faults it is not easy, a prediction about the present seismic hazard in Calabria can hardly be proposed.

On the other hand, the tectonic setting in the central Mediterranean region (**Figure 5**) suggests that the present reduced mobility of the Calabrian Arc may increase stress in the faults located at the boundaries of the Hyblean block (Sicily). This hypothesis is based on the fact that the compressional regime induced by the convergence of the surrounding plates is accommodated by the extrusion of the Calabrian wedge and the Hyblean block (**Figure 9**). The relative motion between these two wedges is mainly allowed by the dextral Vulcano-Syracuse

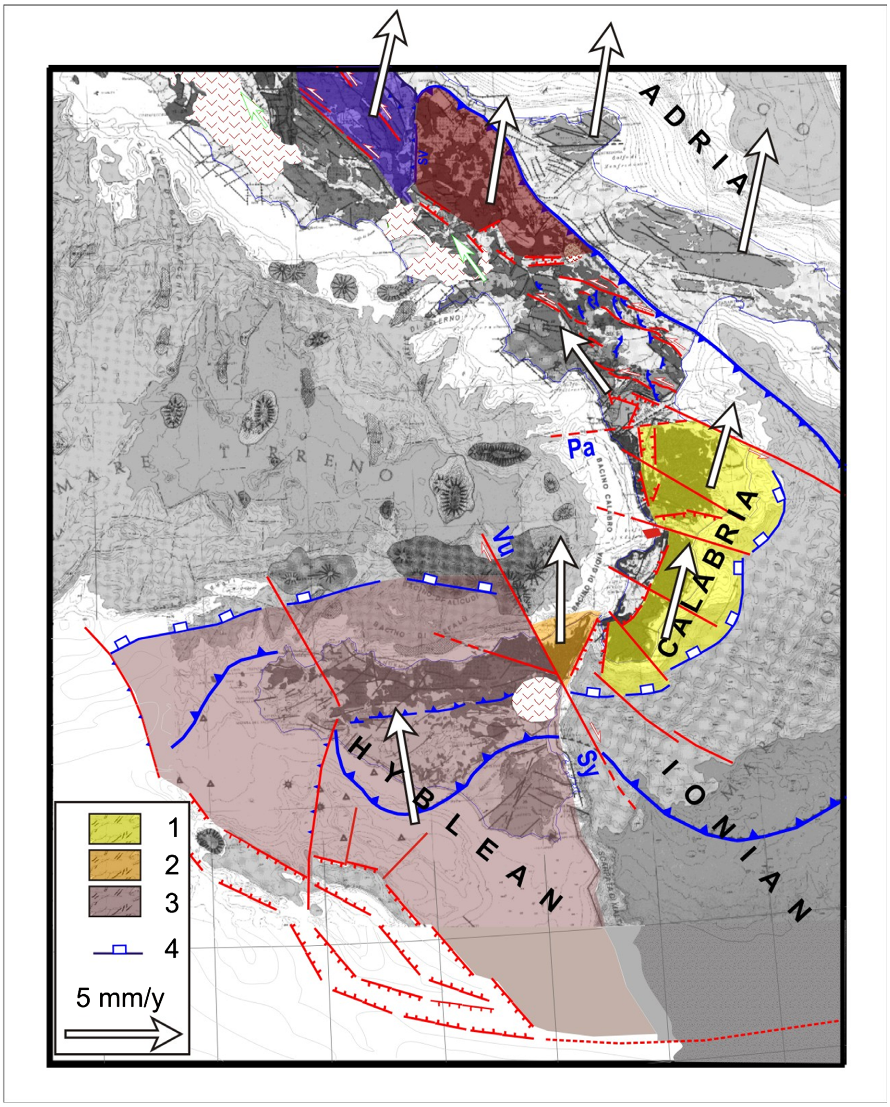

Figure 9. Tectonic-kinematic context in the central Mediterranean region, reported on the Geological Map of Italy ([45], modified). 1) Calabrian wedge 2) Peloritani block 3) Hyblean wedge 4) Outer front of the Alpine units. White arrows indicate the proposed kinematics with respect to Eurasia. The convergence between the confining plates is accommodated by the opposite extrusions of the Calabrian and Hyblean wedges. Pa = Palinuro fault, Vu-Sy = Vulcano-Syracuse fault system. Other symbols as in **Figure 5**.

fault system, where very strong earthquakes occurred (e.g., 1169 M = 6.5; 1693 M = 7.3).

In this context, one can expect that when the decoupling of the Calabrian wedge becomes more difficult (due for instance to the upward flexure of the Ionian domain induced by the westward push of the Anatolian-Aegean system) the probability of major earthquakes along the boundaries of the Hyblean block may increase. This hypothesis is compatible with the fact that since 1948 seismic activity around the Hyblean block has undergone a significant increase (**Figure 10**).

Another aspect of the time distribution of Calabrian major shocks which could help us to recognize the location of next events in that zone is the fact that

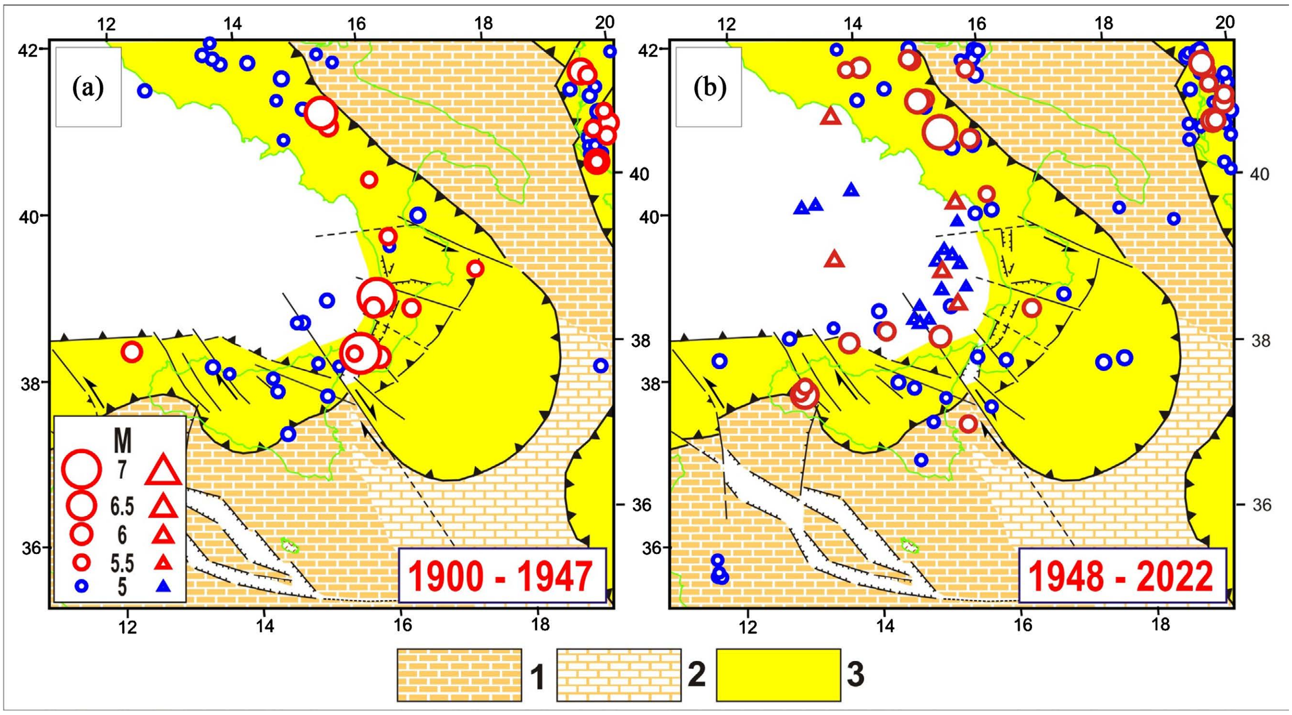

Figure 10. Seismic activity in the Sicily and Calabria zones before and after 1947. 1) Nubia-Adriatic domain 2) Oceanic Ionian domain 3) Orogenic belts. Circles and triangles respectively indicate focal depths lower and greater than 60 km. Other symbols as in Figure 5. Seismicity data as in Figure 4.

seismic activity does not occur randomly in space and time, but rather tends to alternate periods of activation of the northern and southern parts of Calabria, mostly separated by long periods of very low activity (Figure 11).

For instance, one could note that the main seismic crises in the northern part of Calabria (1600-1659 and 1832-1884) preceded the ones in the southern part (1766-1791 and 1885-1913).

If this pattern would prosecute, one may expect that next major shocks will more probably affect northern Calabria (Figure 11).

To recognize the possible implications the ongoing seismic quiescence in the northern RMU wedge (Figure 8) may have on the seismic hazard in that zone it may be useful to make some considerations on how seismic activity in the northern RMU wedge may be influenced by the activation of the main fault systems in the central Apennines. When the decoupling between the outer and inner sides of the Latium-Abruzzi carbonate platform (LA) is allowed by the seismic activation of the Fucino fault system, the consequent northward acceleration of the eastern LA block induces an increase of stress in the entire RMU wedge. This perturbation increases earthquake probability at the northern boundaries of this wedge (*i.e.*, the Alta Valtiberina trough, the Romagna fault and the Rimini-Ancona thrust front), as suggested in particular by the spatio-temporal distribution of events that followed the 1915 Fucino shock ($M = 7.1$, Figure 12).

Such seismicity pattern may be explained as an effect of post-seismic relaxation in the framework of the tectonic interpretation here proposed [47] [48] [49].

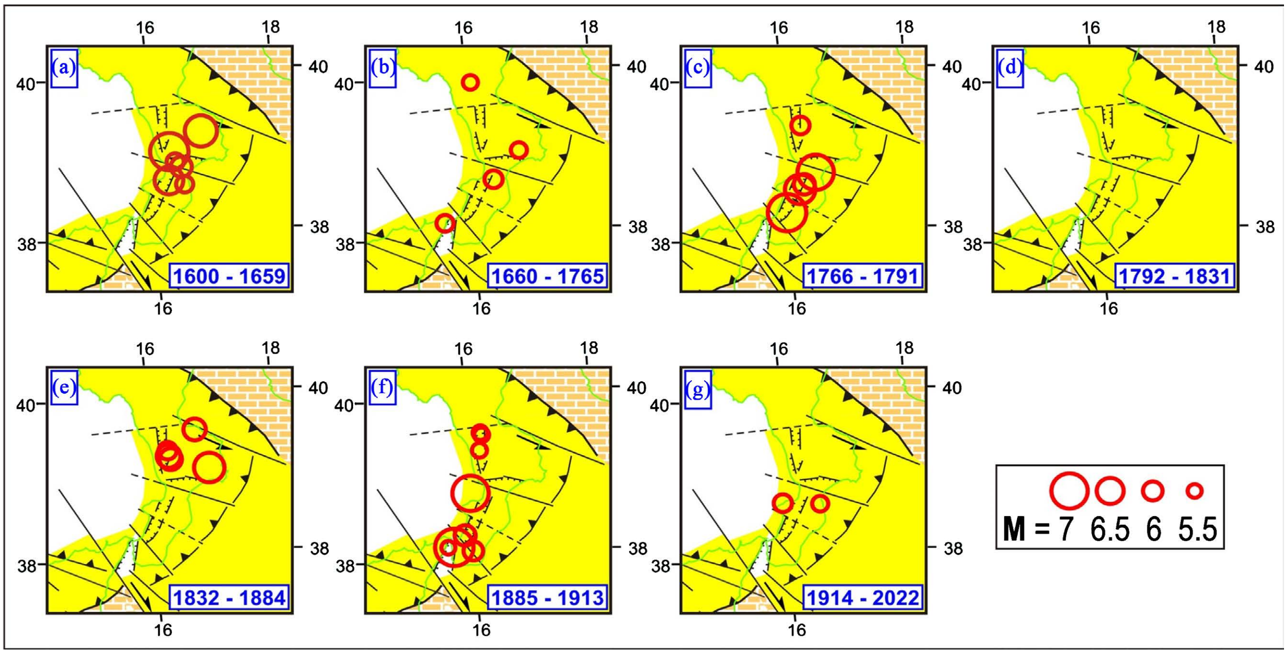

Figure 11. Distribution of major earthquakes (M ≥ 5.5) in 7 periods, during which seismicity seems to concentrate in the Northern Calabria ((a), (e)), Central-Southern Calabria ((c), (f)) or to almost disappear ((b), (d), (g)).

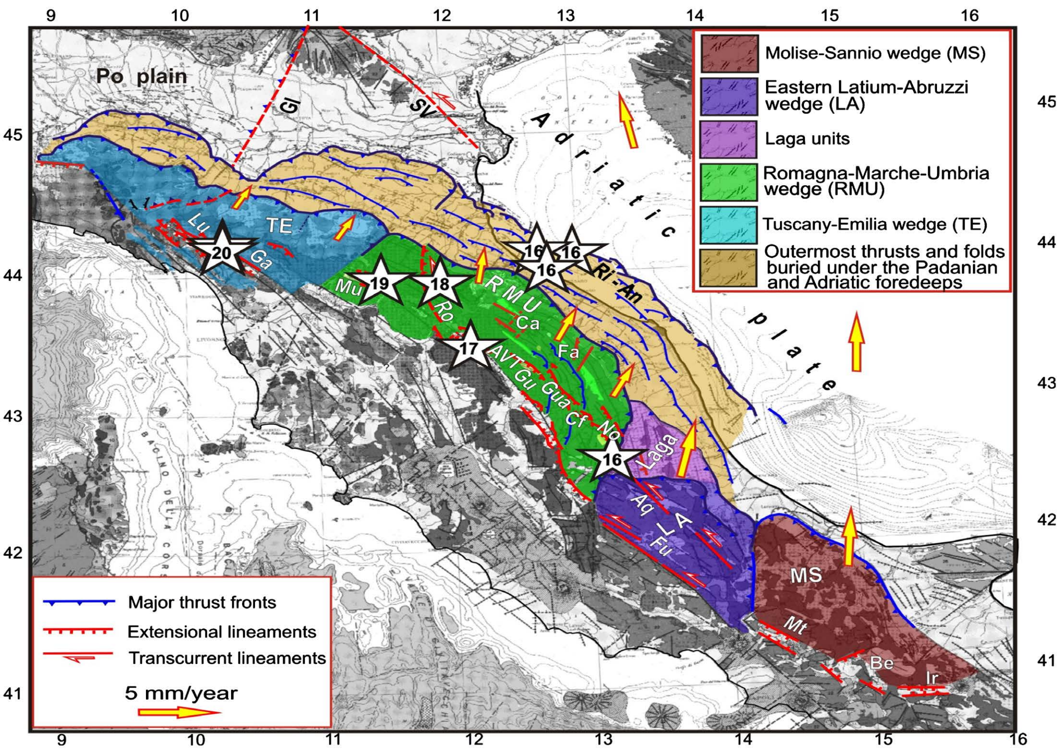

Figure 12. Distribution of main earthquakes (stars and occurrence year) with M ≥ 5.5 in the northern Apennines (1916-1920, see Figure 13 for details) after the strong 1915 shock (M = 7.1) in the Fucino fault [32]. Colours identify the outer mobile sectors of the Apennine belt reported on the Geological Map of Italy ([45], modified). Aq = L'Aquila fault, AVT = Alta Valtiberina trough, Be = Benevento fault, Ca = Cagli fault, Cf = Colfiorito fault, Fa = Fabriano fault, Fu = Fucino fault, Ga = Garfagnana trough, Gi = Giudicarie fault system, Gu = Gubbio fault, Gua = Gualdo Tadino fault, Ir = Irpinia fault, Lu = Lunigiana trough, Mt = Matese fault, Mu = Mugello trough, No = Norcia fault, Ro = Romagna fault, Ri-An = Rimini-Ancona thrust front. The yellow arrows indicate the kinematic field [33] [46].

The short-term tectonic kinematic setting that could have developed during the 1916-1920-time interval is tentatively sketched in **Figure 13**. The fact that after the 1915 Fucino earthquake the first seismic effects involved the Rimini thrust

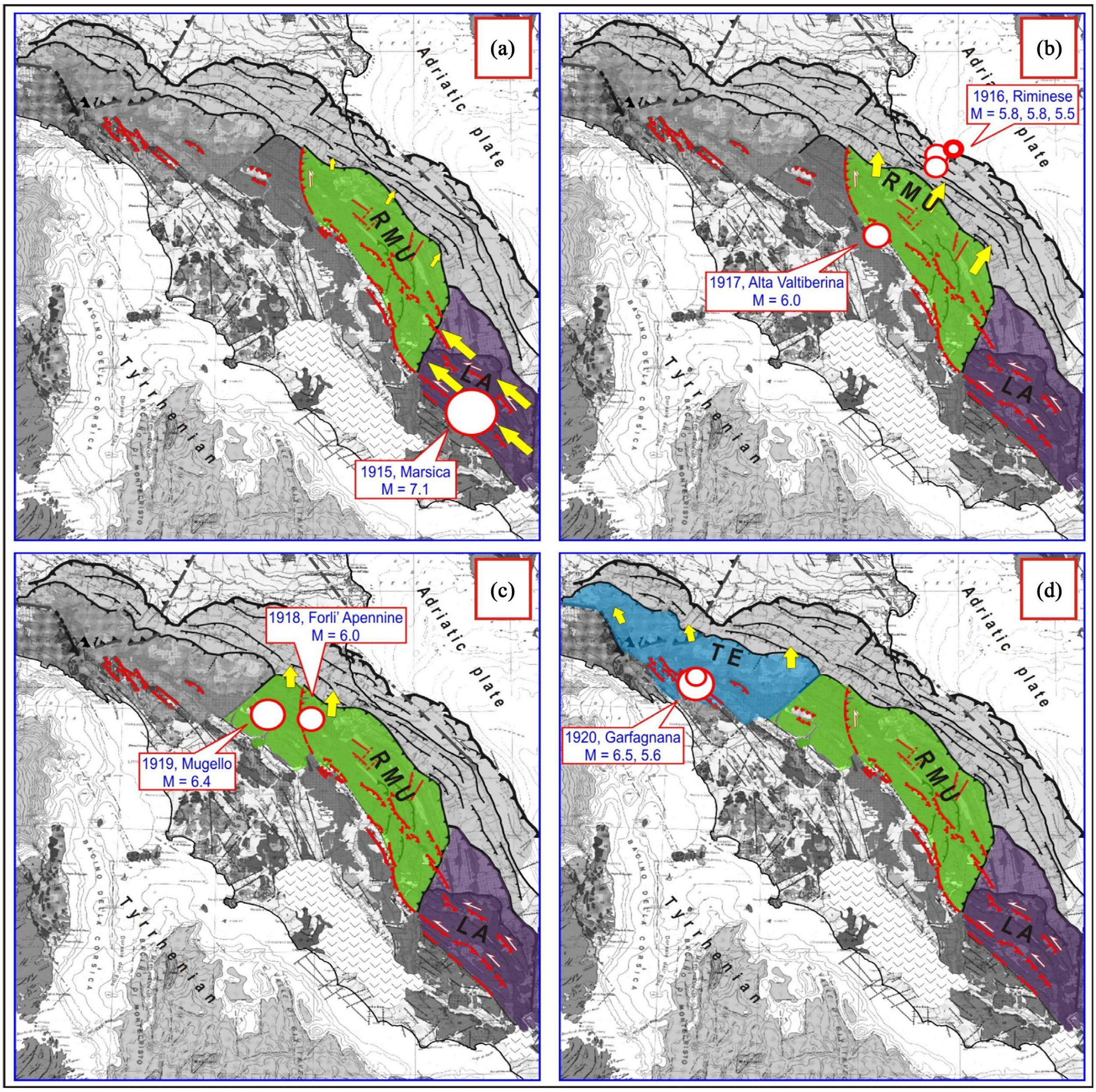

Figure 13. Tentative reconstruction of the short-term kinematic pattern in the northern Apennines (reported on the Geological Map of Italy [45], modified) that was triggered by the earthquakes occurred from 1915 to 1920 [32]. (a) The Fucino event with more than 1 m of sliding at the fault [47] decouples the LA block (violet) from the inner Tyrrhenian belt triggering the acceleration of this block (yellow arrows) and of the southern RMU wedge (green). (b) The increase of compressional stress at the northern boundary of RMU causes the three Riminese shocks (1916). The displacement allowed by this thrusting favours the motion of this wedge, increasing stress in the AVT trough, where the 1917 earthquake took place. (c) Once decoupled at its outer and inner boundaries, the northern RMU wedge moves faster, favouring its decoupling from the Emilian Apennines, allowed by the Romagna Apennine shock (1918). The previous earthquakes increased stress in the northernmost sector of the RMU wedge (green), causing the Mugello earthquake (1919). (d) The acceleration reaches the Tuscany-Emilia Apennines, causing the activation of the Garfagnana fault (1920).

front, without affecting the Norcia-Colfiorito, Gualdo Tadino and Gubbio faults, suggests that the post-seismic acceleration involved the entire RMU wedge. This hypothesis is also supported by the fact that strong shocks also occurred in the Mugello zone (1919) and even reached the northernmost Apennine sector (Garfagnana, 1920).

When instead, the decoupling between the outer and inner sides of the central Apennines is allowed by the activation of the L'Aquila fault system (**Figure 3**), only a smaller portion of the central Apennines wedge accelerates and consequently only a narrower part of the RMU wedge is pushed northward. This kinematic pattern increases stress along the faults that are aligned with the L'Aquila fault (Norcia-Colfiorito, Gualdo Tadino, Gubbio, Valle Umbra), along the inner boundary of the southern RMU wedge and possibly along more external fault zones (Fabriano and Cagliese). A significant example of this seismotectonic mechanism developed in the period 1703-1706, when three strong earthquakes activated the l'Aquila fault system (**Figure 14(a)**), from the Maiella to the Norcia zones, and then developed by a series of shocks in the southern RMU wedge (**Figure 14(b)**), along the faults aligned with the L'Aquila fault (Norcia-Colfiorito 1719, 1730, Fabriano 1741, Valle Umbra 1747, Gualdo Tadino 1751). The migration of seismicity prosecuted in the northern RMU wedge (**Figure 14(c)**, Romagna 1768, 1781, Cagliese 1781, Riminese 1786, Alta Valtiberina 1789, Umbria 1791) and finally reached the northermost sector of the belt (**Figure 14(d)**, involving western Tuscany and the Emilia Apennines, with earthquakes in the Pavese (1828), Reggiano (1831, 1832) and Lunigiana (1834, 1837) zones.

The two examples described above suggest that major earthquakes in the northern RMU fault zones are most likely induced by the activation of the Fucino fault, especially when the magnitude of the triggering shock is very high, as occurred in 1915 (M = 7.1). This last consideration is supported by the fact that after the 1654 Fucino earthquake (M = 6.3) the activation of the Northern RMU boundaries only developed during a longer time interval (1661-1690) with respect to the very short 1915-1920 seismic sequence (**Figure 8** and **Figure 12**).

It can be noted that the time distribution of major seismic crises in the central Apennines (**Figure 8**) was characterized by an interesting regularity, concerning the fact that since 1600 the L'Aquila and Fucino fault systems activated alternatively (Fucino 1654, L'Aquila 1703-1706, Fucino 1915, L'Aquila 2009-2016). This alternance is confirmed by what happened in the previous centuries (**Figure 15**), when major earthquakes in the central Apennines occurred in 1258 (Fucino), 1315 (L'Aquila), 1349 (Fucino), 1461 (L'Aquila). Such evidence could suggest that the next major shock in the central Apennines will involve the Fucino fault system and that such event will not occur within a short time interval (tens of years).

Other insights into the possible next seismic behaviour of the northern Apennines may be gained by considering the similarity between the ongoing sequence (1930-2022, **Figure 16**) and the one that developed in the period 1707-1751,

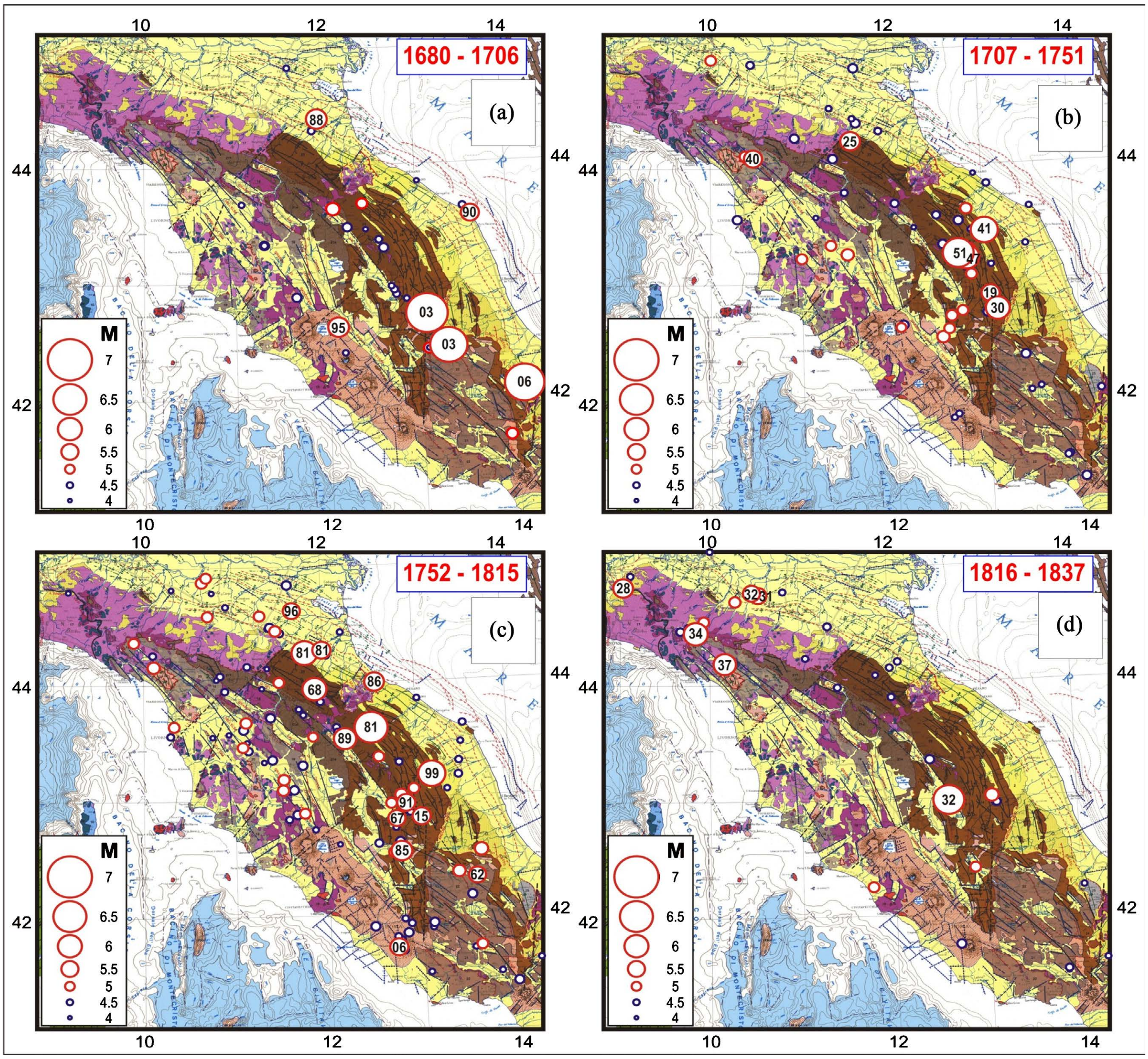

Figure 14. Distribution of the major earthquakes that followed the main 1703 shocks in the L'Aquila and Norcia faults, during the three periods considered, reported on the Tectonic Map of Italy [45]. Data from [32].

Figure 14(b), both involving the activation of the fault systems located in the southern RMU wedge. Tentatively assuming that the present situation will evolve as the one that followed the 1703-1706 seismic crisis in the L'Aquila fault, one could recognize the northern boundaries of the RMU wedge (Alta Valtiberina, Cagli, Romagna and Rimini-Ancona) as the zones most prone to seismic activity in the next decades, as occurred in the 1752-1815 period (**Figure 14(c)**).

Taking into account the seismicity patterns shown in **Figure 8**, one could identify some features that may be useful to recognize the present seismic hazard in the northern RMU wedge. In particular, one could note that the activations of these zones mainly occurred some years after major shocks in the Fucino fault zone, as in the first and in the fourth sequences, or after a number of shocks

HELLENIDES ALBANIDES SOUTHERN DINARIDES M ≥ 6	CALABRIA M ≥ 5.5	SOUTHERN APENNINES M ≥ 5.5	CENTRAL APENNINES M ≥ 5.5	SOUTHERN RMU M ≥ 5.5	NORTHERN RMU M ≥ 5.5	EASTERN ALPS NORTHERN DINARIDES M ≥ 5.5
1237(6.2) 1270(6.7) 1273(6.6) 1278(6.6) 1359(6.0) 1380(6.1) 1444(6.4) 1451(6.1) 1469(6.6) 1471(6.1) 1481(6.0) 1482(6.2) 1508(6.5) 1513(6.5) 1514(6.5) 1515(6.7) 1516(6.0) 1520(6.0) 1521(6.3) 1554(6.1) 1559(6.0) 1563(6.1) 1577(6.2) 1592(6.6)	1509(5.6)	1273(5.8) 1293(5.8) 1361(6.0) 1456(7.2) 1466(6.0) 1561(6.3,6.7)	1258(5.6) 1315(5.6) 1348(5.6) 1349(6.8,6.3) 1461(6.5)	1277(5.6) 1279(6.2) 1298(6.3) 1328(6.5) 1599(6.1)	1269(5.6) 1279(5.5) 1352(6.3) 1389(6.0) 1428(5.5) 1458(5.8) 1483(5.7) 1584(6.0)	1323(6.0) 1348(6.6) 1403(5.6) 1502(5.7) 1511(6.3,5.6,6.3) 1551(6.3) 1574(5.6)

Figure 15. Seismicity patterns of the peri-Adriatic zones (see **Figure 7**) in the period 1200-1599 (Seismicity data from [30] [31] [32] [50]-[56]).

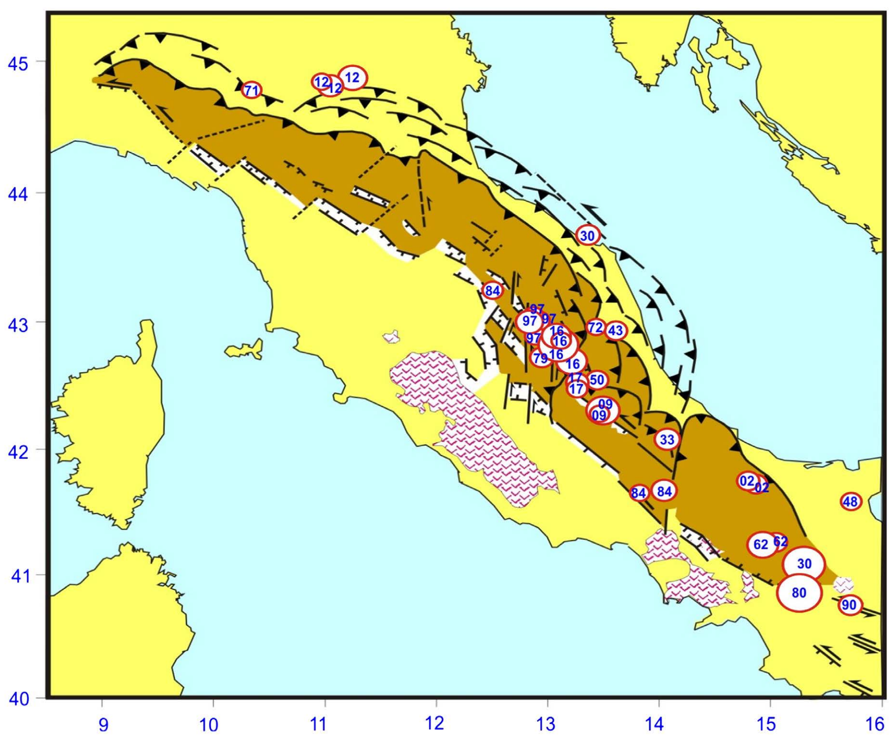

Figure 16. Main earthquakes (red circles M ≥ 5.5) occurred since 1930 in the Apennine belt. Data from [32].

in the southern RMU wedge, as in the second and third sequences. This last possible precursory pattern is similar to the one that has so far developed in the ongoing sequence, which includes five earthquakes with M ≥ 5.5 in the southern RMU wedge (1943-1997), followed by the 2009 (M = 6.3), 2016 (M = 6.5, 6.0) and 2017 (M = 5.6) earthquakes in the l'Aquila and Norcia faults. The ongoing seismic quiescence in the northern RMU wedge, so far lasted 92 years (1930-2022) for M > 5.5, is longer than the previous ones in the period here considered (all shorter than 82 years, **Figure 8**). Furthermore, one can consider that seismic crises in the northern RMU zones mostly occurred within relatively short time intervals (5 - 30 years, **Figure 8**) from each other. This could imply that the rupture of one fault zone may favour the activation of the other two zones, within some tens of years.

Another interesting feature of the seismicity patterns shown in **Figure 8** is the fact that in the first four sequences the main seismic crises in the northernmost zone (eastern Southern Alps and Northern Dinarides) were preceded by main crises in the northern RMU zones. The only exception occurred in the last ongoing sequence, when the 1976 M = 6.5, 5.9, Friuli earthquakes were not preceded by shocks with M > 5.5 in the northern RMU zones. However, it is worth considering that in 1972 the Ancona zone was hit by a long series of earthquakes with magnitudes comprised between 4.5 and 5.5 for a period of several months.

The possibility that seismic activity in the northern Adriatic boundaries is influenced by major shocks in the northern RMU boundaries is also supported by the fact that this connection may have a plausible tectonic explanation. The Adria plate, stressed by the confining plates, tries to move roughly northward, carrying the outer side of the Apennine belt. This process encounters a relatively low resistance to mobilize the belt sector which is parallel to Adria (Southern Apennines, Central Apennines and RMU wedge). However, the resistance to mobilize the Tuscany-Emilia Apennines is much higher since that belt sector is not parallel to Adria and, in addition, it is close to the northernmost Apennines sector (Ligurian units), not characterized by yielding evaporitic layers at the bottom of the sedimentary cover. This last consideration may explain why the activation of the Alta Valtiberina and Rimini-Ancona fault zones make more likely the activation of the Romagna decoupling fault.

3. Conclusions

The Adria plate, stressed by the convergence of the confining domains, tries to move roughly northward. This motion mainly develops in a discontinuous way, exploiting the decoupling earthquakes that occur at the peri-Adriatic fault zones. Each strong shock triggers a perturbation of the strain field which propagates through the plate, increasing stresses (and earthquake probability) in the still blocked peri-Adriatic faults. The hypothesis that this process migrates from the southern boundary zones to the northern front, in the eastern Southern Alps, may be compatible with the space-time distribution of major shocks since 1600

(**Figure 8**), that we tentatively interpret as 5 migrating seismic sequences. Each migration may be triggered by strong seismic crises at the collision zone between the Adria plate and the Aegean-Pelagonian system (Cephalonia, Epirus, Albanides and Southern Dinarides). These decoupling events induce stress increases in the Calabrian wedge and then in the Apennine belt, where major earthquakes progressively migrate from the southern to the northern sectors, to finally reach the Northern Dinarides and the eastern Southern Alps. The activation of the northern Apennines faults may be influenced by the main seismic crises in the southern and central Apennines. This hypothesis is supported in particular by the seismicity patterns that followed the two main seismic phases in the southern-central Apennine belt (1688-1703 and 1910-1915, **Figures 12-14**).

The distribution of main shocks in the northern Apennines presents different patterns depending on which fault system is activated in the central Apennines. This may be due to the fact that when the Fucino fault is activated, the decoupled sector of the central Apennines is wider than the one that is decoupled by a major shock in the L'Aquila fault. The seismicity pattern that followed the strong 1915 Fucino earthquake (**Figure 12**) suggests that the activation of such fault may cause the acceleration of the whole RMU wedge, inducing seismicity along its northern boundaries (Alta Valtiberina, Romagna and Rimini-Ancona zones). When instead the L'Aquila fault is activated, the subsequent seismicity in the northern Apennines first involves the series of faults aligned with the L'Aquila one. Then, seismicity progressively affects the other northernmost Apennine zones.

Some repeated features in the distribution of major earthquakes (**Figure 8**) can be recognized in the presumed sequences, as described in the following.

- The space-time distribution of seismicity since 1200 (**Figure 8** and **Figure 15**) indicates that the Fucino and L'Aquila faults have been activated in an alternative way. The relatively high number of cases in which such alternance occurred could allow to tentatively recognize which of those two faults will be activated next.
- The last (ongoing) sequence (1930-2022) is characterized by very low seismic activity in the Calabrian and northern RMU wedges (**Figure 8**). In Calabria, the fact that the present quiescence (114 years for $M \geq 6$) is slightly shorter than the longest previous quiescence (124 years) could suggest a dangerous situation, but it must be considered that the stop of seismic activity (since 1948 for $M \geq 5.5$) may be conditioned by the considerable increase of compressional stress that this zone has undergone in response to the large westward displacement of the Anatolian-Aegean-Pelagonian system since 1939. Considering this possibility and the difficulty of quantifying how long this transient stress perturbation will inhibit seismic activity in Calabria, one must be aware that any estimate of the present seismic hazard may be affected by considerable uncertainty. On the other hand, the tectonic setting in the central Mediterranean region (**Figure 5**) suggests that the present reduced mobility of the Calabrian Arc may induce an increase of stress (and of

seismic hazard) in the Sicily-Hyblean block (**Figure 10** and **Figure 11**).

- The distribution of major earthquakes in the last sequence (1930-2022, **Figure 16**) is similar to the one that occurred in the period 1707-1751 (**Figure 14(b)**), after the 1703-1706 strong seismic phase in the L'Aquila fault system. This could imply that in the next 15 - 35 years seismic activity in the northern Apennines may involve major shocks in the northern RMU boundary zones, as occurred in the period 1768-1789 (**Figure 14(c)**).
- The seismicity patterns shown in **Figure 8** indicate that since 1600 the activations of the three northern RMU boundary zones (Alta Valtiberina trough, Romagna shear zone and Rimini-Ancona thrust front) have always occurred within short time intervals one from the other. This could help to recognize when seismic hazard in those zones may undergone a significant increase.
- In the first four sequences (**Figure 8**), the main seismic crises in the eastern Southern Alps and Northern Dinarides were preceded by major earthquakes in the northern RMU boundaries. This feature, whose tectonic meaning is discussed in the text, could be useful to recognize when seismic hazard can increase in the northernmost peri-Adriatic zones.

The possibility of identifying seismic prone zones using the regularities in the seismicity distribution tentatively identified in this work is obviously conditioned by the number of the cases involved in the period here considered. At present the presumed completeness of seismic catalogues suggest the use of the last 4 centuries. This strongly encourages the performance of further studies on historical seismicity to try an extension of the time interval that can be taken into account for this kind of analyses.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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