Seismic hazard in Tuscany: which best defence strategy?

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Abstract. The hypothesis that the probability of major earthquakes in a given zone is strongly influenced by the space-time distribution of previous seismic events in the surrounding area is supported by numerous and significant pieces of evidence. This work describes a particularly clear example of this phenomenon that occurred in the central-northern Apennines during the period 1915-1920. The fact that the strong 1915 Fucino earthquake in the central Apennines was followed by an exceptional seismic reaction of the northern Apennines (6 events of magnitude greater than 5.5 in the 1916-1920 time interval) is consistent with the active tectonic setting of these zones. Furthermore, it can be demonstrated that the time occurrence of each event in the northern Apennines is compatible with the arrival of the highest values of the perturbation induced by the previous shocks, as computed by numerical modelling of postseismic relaxation.
Keywords: Postseismic Relaxation, Seismotectonics, Northern Apennines, Seismic Hazard.

Conceptual basis

Deformation in the Apennine belt mainly develops by the seismic and aseismic activation of major shear fractures (faults). It is known that each strong earthquake triggers a perturbation of the strain field that propagates in the surrounding regions with velocities comprised between tens and more than 100 km/year (e.g., Viti et al., 2003). When in one of such zones the increase of strain and strain rate has an adequate amplitude and characteristics compatible with the nature and geometry of the faults, induced earthquakes may occur. This implies that the space-time distribution of major shocks may considerably influence the deformation in the crust and thus seismic activity in the zones tectonically connected with the ones previously activated. The effects of this interaction between seismic sources, and in particular the tendency of this phenomenon to repeatedly occur with similar features in the same zones, have been recognized in some sectors of the Mediterranean area (Mantovani et al., 2008, 2010, 2012a,b). For instance, it has been pointed out that in the last two centuries (i.e. the most complete and reliable part of the seismic catalogue) all major earthquakes in the Southern Apennines have been preceded within few years by strong events in the Southern Dinarides, a zone lying on the opposite side of the Adriatic sea. Another significant interrelation has been recognized between the strong shocks of Calabria and the ones of the Hellenic Arc (from Crete to Cefalonia island) for the time interval 1600-2011 (Mantovani et al., 2008, 2012a,b).

The influence of the above phenomenon (postseismic relaxation) on the space-time distribution of major earthquakes in the whole central Mediterranean region is suggested by the analysis of the related seismic history since 1600 (Mantovani et al., 2008, 2012b; Viti et al., 2009). In particular, it has been pointed out that the most intense seismicity tends to systematically migrate form the Hellenic Trench to the northern Adriatic zones (Eastern Alps and Northern Dinarides) through the periAdriatic regions. In the next paragraph attention is focused on the examples of the above phenomenon in the study area.

Tectonic processes and seismicity in the Apennine belt

Present knowledge on geodynamics and recent evolution of this area (Mantovani, 2005; Mantovani et al., 2007, 2009, 2011; Viti et al., 2006, 2009, 2011) suggests that main deformation in the Apennine belt and the related seismic activity are generated by the relative motion between the outer sector of the belt (driven by the Adriatic plate) and the almost fixed inner part of the belt (Fig.1).

During the last million of years the oblique divergence between these two sectors of the Apennines causes the sinistral extensional and transtensional deformation in the axial part of the belt, with the formation of normal faults and troughs, associated with the strongest earthquakes, form the Irpinian zone to the Lunigiana-Garfagnana troughs (Viti et al., 2006; Mantovani et al., 2009).

The decoupling between these two sectors is periodically accelerated by the strong earthquakes that hit the axial part of the belt. A number of papers (Mantovani

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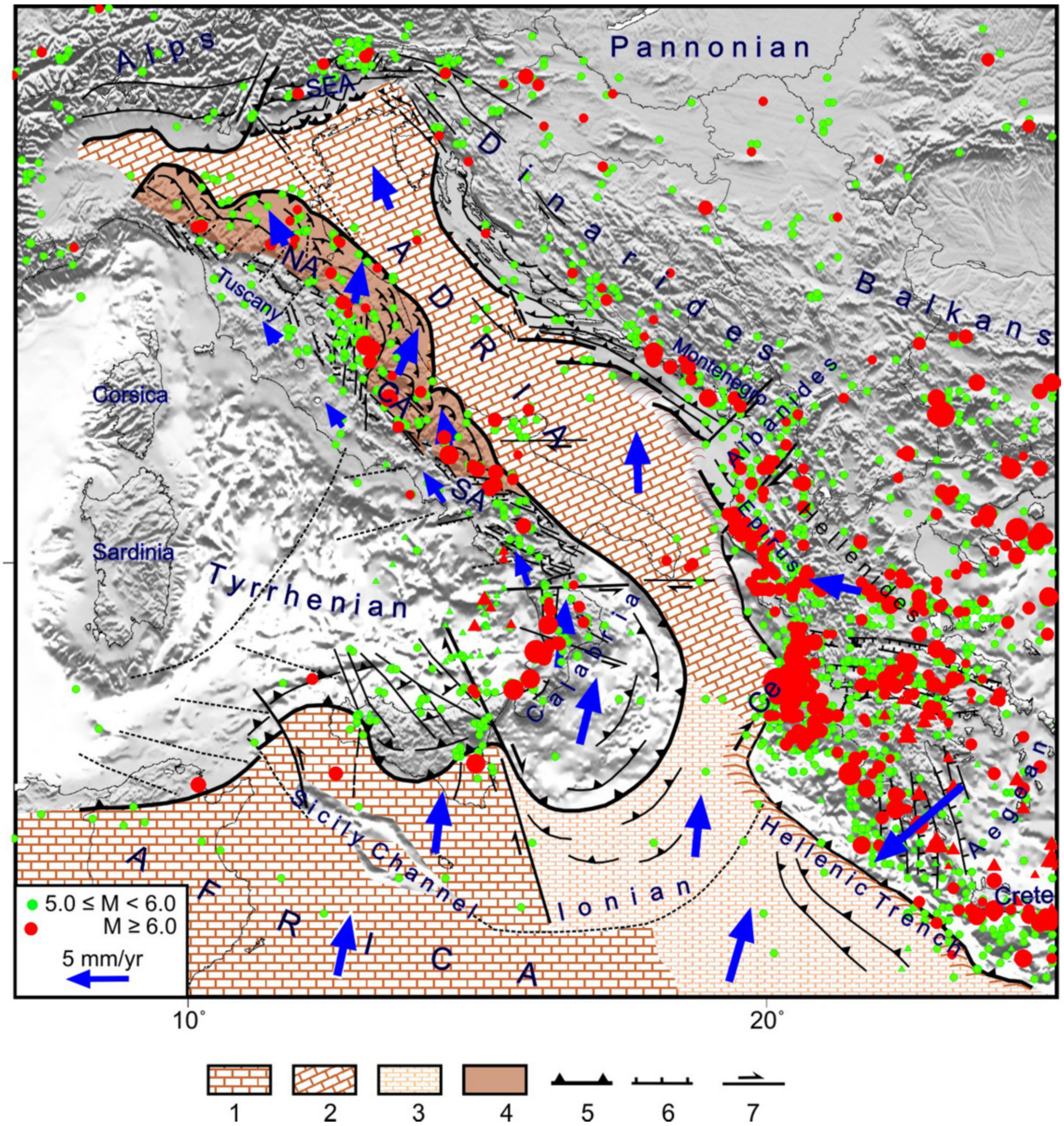

Fig.1 - *Tectonic setting and block kinematics in the central Mediterranean, compatible with the post-middle Pleistocene deformation pattern (Mantovani et al., 2009). 1-2) African and Adriatic continental domains. 3) Ionian oceanic domain. 4) Outer sector of the Apennine belt dragged by the Adriatic plate. 5,6,7) Main compressional, extensional and strike-slip lineaments respectively. Blue arrows depict the long term (Pleistocene) kinematic pattern with respect to Eurasia. Red and green points respectively indicate the epicentres of major and minor earthquakes occurred in the 1600-2011 time interval. CA = Central Apennines, Ce = Cephalonia Fault, NA = Northern Apennines, SA = Southern Apennines, SEA = Southern Eastern Alps.*

et al., 2009, 2010, 2012a,b; Viti et al., 2009) has pointed out that this tectonic scheme can plausibly explain the distribution of the strong shocks that have occurred during the four most intense seismic sequences in the Apennine belt (1349-1361, 1456-1461, 1688-1706, 1910-1920).

Important insights into how the interaction between seismic zones is influenced by the propagation of the the postseismic perturbation are provided by the study of the last sequence. The main seismic phase has involved the strong (magnitude M = 7 and intensity I = XI in the MCS scale) 1915 Fucino earthquake (central Apennines) and the series of shocks of M > 5.5 that occurred in the northern Apennines in the 1916-1920 time interval (Fig.2).

The present knowledge of the Apennine tectonic setting suggests that the earthquakes occurred during the above sequence have been associated with the kinematic scheme shown in figure 3. The Fucino event resulted from the activation of the fault system that allowed transtensional decoupling between the eastern (ELA) and western sectors of the Lazio-Abruzzi carbonate platform, in the central Apennines. After this seismic sliding, the ELA block suddenly underwent a roughly NW ward movement of about 1-2 metres, considerably increasing its push on the adjacent northern Apennines, i.e. the Romagna-Marche-Umbria block (RMU in figure 3a). The consequent displacement of the RMU block, roughly NNE ward, first caused transpressional deformation at its outer border (two intense shocks in the Riminese zone, 1916, M = 5.9, 6.1 and I = VIII), where it interacts with the Adriatic domain, and then had effect (1917 Monterchi, Upper Tiber valley, M = 5.9, I = IX-X) at its western side, where it separates from the inner part of northern Apennines (Fig.3b). This phenomenon has then affected the northern sector of the RMU block (Fig.3c), producing an earthquake in the Romagna Apennines (1918, M = 5.9, I = IX) and in the Mugello basin (1919, M = 6.3, I = X), and then the Tuscany-Emilia block (TE in figure 3d), causing a strong earthquake in the Lunigiana-Garfagnana zone (1920, M = 6.5, I = X).

In the following period (1921-1930), other numerous moderate to intense shocks have occurred along the

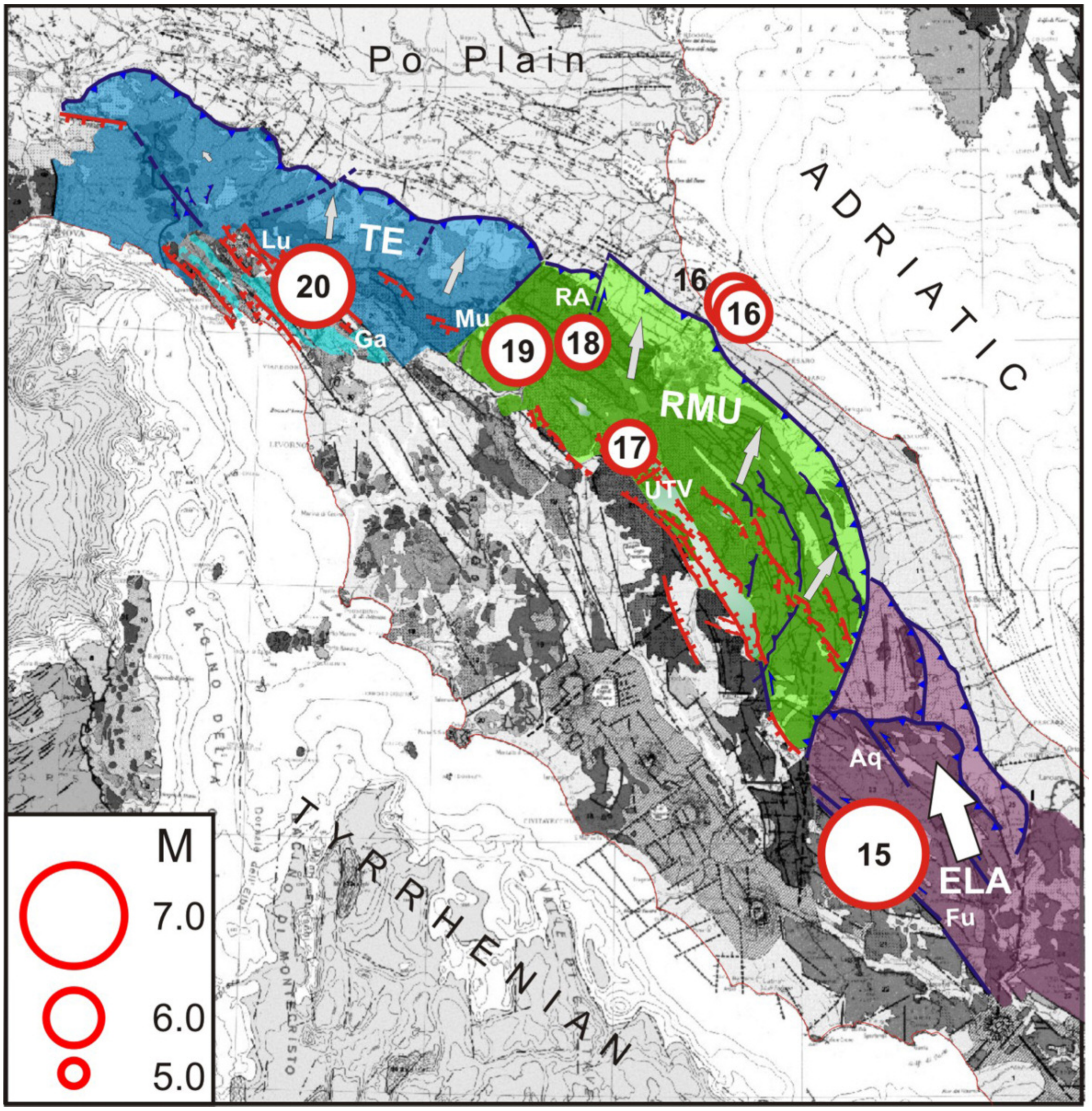

Fig.2 - *Epicentres (circles) of the main shocks occurred from 1915 to 1920, drawn on the tectonic/kinematic sketch of the central-northern Apennines (Mantovani et al., 2011, 2012b). The circle size is related to the magnitude (M) of the earthquake (scale on the bottom left). The number inside the circle indicates the year of the shock: January, 13 1915 Fucino (Avezzano), M = 7; May, 17 and August, 16 1916 Riminese, M = 5.9 and M = 6.1 respectively; April, 26 1917 Upper Tiber valley (Monterchi), M = 5.9; November, 10 1918 Romagna Apennines, M = 5.9; June, 29 1919 Mugello, M = 6.3; September, 7 1920 Lunigiana-Garfagnana, M = 6.5. Colours indicate the two main mobile blocks of the northern Apennines: Romagna-Marche-Umbria (RMU, green) and Toscana-Emilia (TE, blue). The belt-parallel shortening of the Apennines is produced by the large-scale geodynamic context shown in figure 1 (Mantovani et al., 2009). The outward extrusion of RMU and TE blocks, indicated by small gray arrows, is induced by the push (large arrow) of the eastern sector of the Lazio-Abruzzi platform (ELA). Extensional tectonic features (normal faults) are reported in red; strike-slip faults and compressional lineaments (reverse faults, thrusts and folds) in blue. Aq = L'Aquila fault system, Fu = Fucino fault system, Ga = Garfagnana, Lu = Lunigiana, Mu = Mugello, RA = Romagna Apennines, UTV = Upper Tiber valley.*

outer border of the RMU and TE blocks; the most significant have hit the Senigallia zone in 1924 (M = 5.3), the Bologna zone in the 1929 (M = 5.3) and again the Senigallia zone in the 1930 (M = 5.8).
The above example provides an important evidence on the fact that seismic sources may interact. Indeed, one could hardly explain why such an anomalous seismic behaviour of the northern Apennines (concerning the number and magnitude of shocks) has just followed the strongest earthquake ever occurred in the Fucino fault system, without assuming an underlying tectonic connection between the two zones involved.

Quantification of the postseismic perturbation

The hypothesis that the earthquakes occurred in the 1915-1920 time interval are related to each other by a tectonic mechanism and postseismic relaxation is supported by the results shown in figure 4, which shows the time pattern of the strain rate induced by all previous events in the zones hit by strong earthquakes in the period considered. Attention is focused on this parameter since it considerably influences the probability of the induced shocks. Indeed, a sudden increase of this quantity may significantly emphasize the brittle behaviour of rocks and thus the arrival of the largest

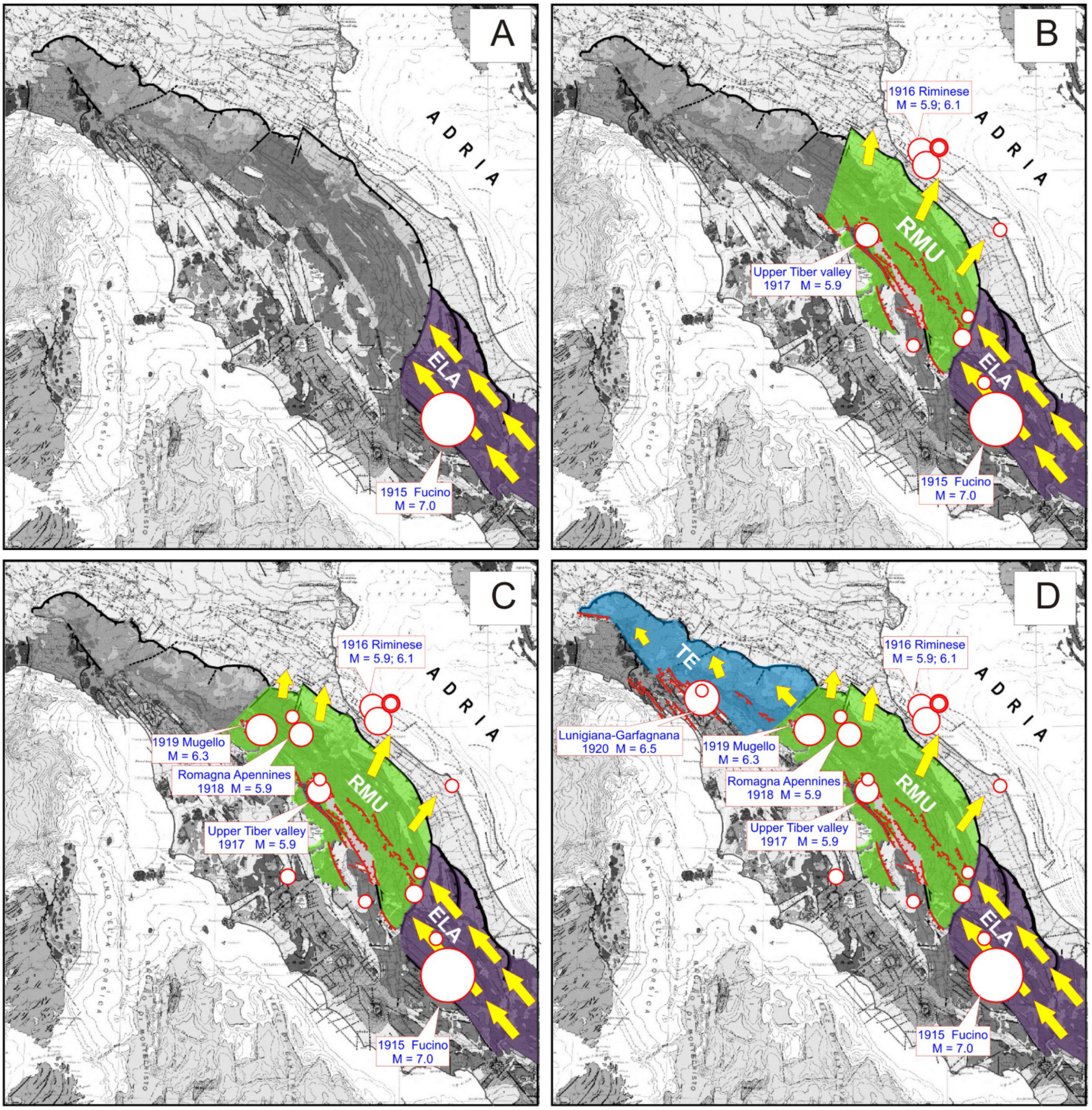

Fig.3 - *Tectonic interpretation of the earthquakes occurred in the central-northern Apennines during the seismic sequence 1915-1920 (tectonic symbols as in figure 2). A) The 1915 Fucino shock causes the decoupling of the eastern Lazio-Abruzzi platform (ELA) from its western sector. B) Stressed by the push of ELA, the Romagna-Marche-Umbria block (RMU) moves outward, inducing seismic activity along its outer and inner margins (1916 Riminese and 1917 Upper Tiber valley shocks respectively). C) The northernmost sector of RMU also moves, causing strong earthquakes along the inner edge of that sector (1918 Romagna Apennines and 1919 Mugello shocks). D) Being pushed by RMU, the Toscana-Emilia block (TE) moves by seismically activating its inner margin (1920 Lunigiana-Garfagnana earthquake).*

values of strain rate would correspond to the highest probability of sliding of the faults involved (e.g., Viti et al., 2003).

Figure 4a shows that in the Riminese zone the two major earthquakes (May and August 1916) has occurred when the strain rate induced by the 1915 Fucino event reached its highest values. The second diagram (Fig. 4b) indicates that the April 1917 Monterchi event, in the Upper Tiber valley, has occurred when the sum of the effects of the Fucino and Riminese events reached the highest values. A good correspondence between the time of the postseismic strain rate peak and the occurrence of the induced shock can be noted as well for the events that struck the Romagna Apennines in November 1918, the Mugello basin in June 1919 and the Lunigiana-Garfagnana in September 1920 (Figs. 4c,d,e respectively).

What comes out from this example is so clear and sig-

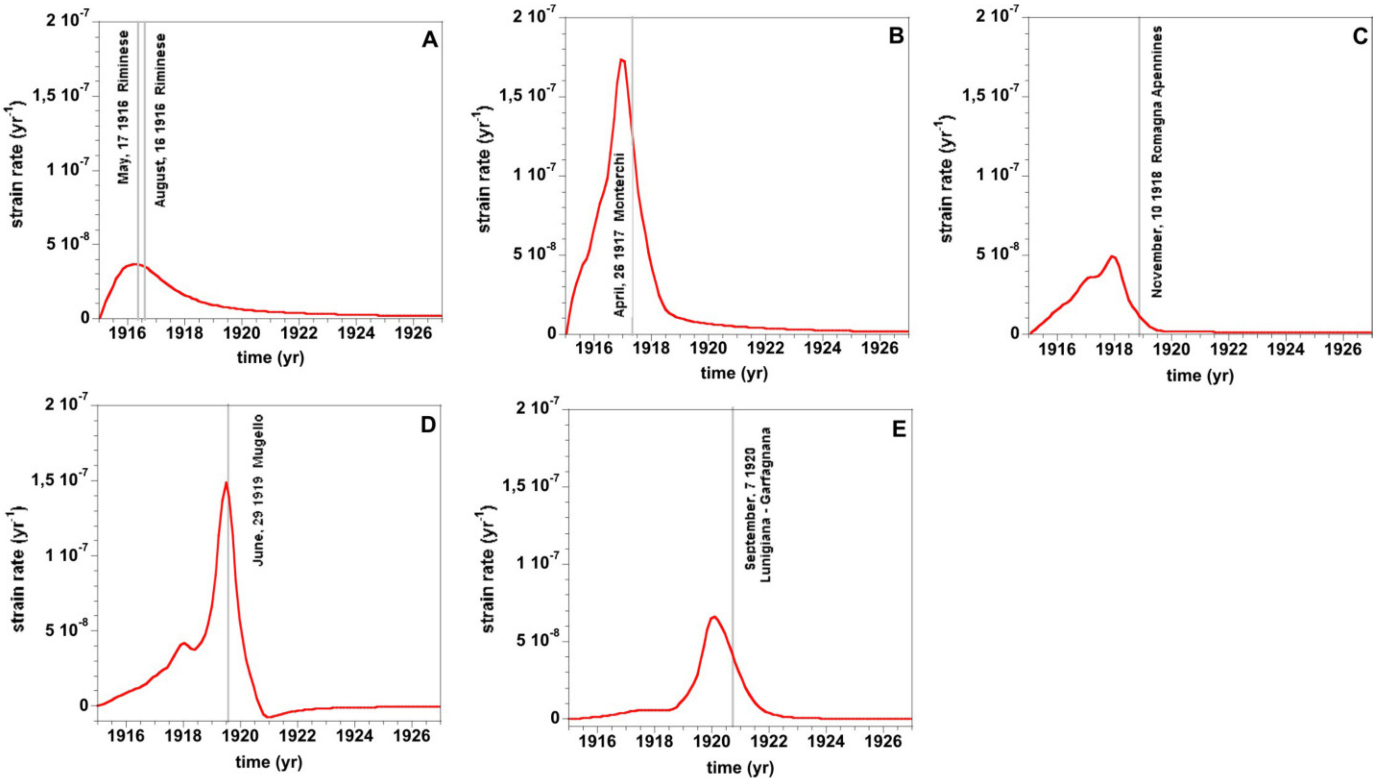

Fig.4 - *Effects of the postseimic perturbation, computed in the zones of northern Apennines hit by the strong earthquakes occurred from 1916 to 1920. The adopted procedure is based on the Finite Element modelling of the stress diffusion in the crust-mantle system. An exhaustive description of the methodology and model parameterization is given in Viti et al. (2003), Cenni et al. (2008), Mantovani et al. (2008, 2012a,b). A) Time pattern of the strain rate induced in the Riminese zone by the 1915 Fucino earthquakes. The vertical line marks the position of the two 1916 Riminese shocks. B) Time pattern of the strain rate induced in the Upper Tiber valley by the Fucino and Riminese earthquakes. The vertical line marks the position of the 1917 Monterchi shock. C) Time pattern of the strain rate induced in the Romagna Apennines by the Fucino, Riminese and Upper Tiber valley earthquakes. The vertical line indicates the position of the 1918 Romagna Apennines shock. D) Time pattern of the strain rate induced in the Mugello zone by the Fucino, Riminese, Upper Tiber valley and Romagna Apennines earthquakes. The vertical line indicates the position of the 1919 Mugello shock. E) Time pattern of the strain rate induced in Garfagnana by the Fucino, Riminese, Upper Tiber valley, Romagna Apennines and Mugello earthquakes. The vertical line indicates the position of the 1920 Lunigiana-Garfagnana shock.*

nificant that removes any reasonable doubt about the fact that major earthquakes in the central and northern Apennines are related to each other. Consequently, the possibility of obtaining significant information on the future distribution of major earthquakes in the study area may now be considered a reasonable objective, at least in the central/northern Apennine belt. However, the recognition of the zones most prone to next strong earthquakes is not always as simple as in the case described above, so that problem must be approached by an accurate analysis of the entire known seismic history in the study area, taking into account the seismotectonic setting and the expected effects of postseismic relaxation in the cases considered. The results so far obtained by such investigation in Tuscany are described in two publications edited by the Regione Toscana (Mantovani et al., 2011, 2012b).

The quantification of the postseismic relaxation triggered by a strong earthquake may allow us to predict its possible effects in the surrounding regions. However such computations are only approximate, due to our insufficient knowledge of the real structural and rheological features of the crust-mantle system in the study area. A considerable help to approach such problem may come from geodetic observations, for example the ones carried out by a Global Positioning System (GPS) network, in that numerical modelling of postseismic relaxation induced by strong periAdriatic earthquakes (Viti et al., 2003; Cenni et al., 2008, 2012) shows that the amplitude of the expected effects may well exceed the accuracy of GPS measurements.

In the framework of an investigation sponsored and cohadiuvated by the Regione Toscana, the data acquired by more than 300 GPS permanent stations are currently analysed to monitor the present velocity and related-strain field in central and northern Italy (Cenni et al., 2012; Mantovani et al., 2012b).

If, for instance, a strong earthquakes would strike the central Apennines again, we could monitor the migration of the postseismic perturbation triggered by such event, making thus much easier to predict when the value of strain rate will be highest in the various seismic zones of the northern Apennines. An example in this direction is given by the analysis of the preseismic, coseismic and postseismic displacement and velocity fields, based on GPS data acquired before and after the April, 6 2009 L'Aquila earthquake, M = 5.8-6.3 (Cenni et al., 2012). In this case, the postseismic perturbation of the GPS velocity field can be detected up to tens of kilometers from the epicentral zone. However, numerical modelling of postseismic relaxation suggests that the amplitude of the strain perturbation induced by the above shock is not sufficient to trigger significant seismic activity in the northern Apennines.

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References

1. Cenni, N.; Viti, M.; Baldi, P.; Mantovani, E.; Ferrini, M.; D'Intinosante, V.; Babbucci, D.; Albarello, D. Short-term (geodetic) and long-term (geological) velocity fields in the Northern Apennines. Boll. Soc. Geol. It. (It. J. Geosciences) 127: 93-104; 2008.

2. Cenni, N.; Mantovani, E.; Baldi, P.; Viti, M. Present kinematics of Central and Northern Italy from continuous GPS measurements. J. Geodynamics, 58:62-72; 2012.

3. Mantovani, E. Evolutionary reconstruction of the Mediterranean region: extrusion tectonics driven by plate convergence. In: Finetti, I.R., ed. Deep seismic exploration of the Central Mediterranean and Italy, CROP PROJECT. Amsterdam: Elsevier; 2005: 705-746.

4. Mantovani, E.; Viti, M.; Babbucci, D.; Albarello, D. Nubia-Eurasia kinematics: an alternative interpretation from Mediterranean and North Atlantic evidence. Ann. Geophysics 50: 311-336; 2007.

5. Mantovani, E.; Viti, M.; Babbucci, D.; Vannucchi, A. Long term prediction of major earthquakes in the Calabrian Arc. Environmental Semeiotics 1: 190-202 ; 2008.

6. Mantovani, E.; Babbucci, D.; Tamburelli, C.; Viti, M. A review on the driving mechanism of the Tyrrhenian-Apennines system: Implications for the present seismotectonic setting in the Central-Northern Apennines. Tectonophysics 476: 22-40; 2009.

7. Mantovani, E.; Viti, M.; Babbucci, D.; Albarello, D.; Cenni, N.; Vannucchi, A. Long-term earthquake triggering in the Southern and Northern Apennines. J. Seismology 14: 53-65; 2010.

8. Mantovani, E.; Viti, M.; Babbucci, D.; Cenni, N.; Tamburelli, C.; Vannucchi, A.; Falciani, F.; Fianchisti, G.; Baglione, M.; D'Intinosante, V.; Fabbroni, P. Sismotettonica dell'Appennino Settentrionale: implicazioni per la pericolosità sismica della Toscana. Firenze: Centro Stampa della Giunta della Regione Toscana; 2011 (http://www.regione.toscana.it).

9. Mantovani, E.; Viti, M.; Babbucci, D.; Cenni, N.; Vannucchi, A. Middle term prediction of earthquakes in Italy: some remarks on empirical and deterministic approaches. Boll. Geofis. Teor. Appl., in press; 2012a.

10. Mantovani, E.; Viti, M.; Babbucci, D.; Cenni, N.; Tamburelli, C.; Vannucchi, A.; Falciani, F.; Fianchisti, G.; Baglione, M.; D'Intinosante V., Fabbroni, P. Potenzialità sismica della Toscana e criteri di priorità per interventi di prevenzione. Firenze: Centro Stampa della Giunta della Regione Toscana, www.regione.toscana.it; 2012b.

11. Viti, M.; D'Onza, F.; Mantovani, E.; Albarello, D.; Cenni, N. Postseismic relaxation and earthquake triggering in the southern Adriatic region. Geophys. J. Int. 153: 645-657; 2003.

12. Viti, M.; Mantovani, E.; Babbucci, D.; Tamburelli, C. Quaternary geodynamic evolution and deformation pattern in the Southern Apennines: implications for seismic activity. Boll. Soc. Geol. It. (It. J. Geosciences) 125: 273-291; 2006.

13. Viti, M.; Mantovani, E.; Babbucci, D.; Tamburelli, C.; Falciani, F.; Vannucchi, A. Stime avanzate di pericolosità sismica nell'Appennino settentrionale. Etruria Natura 6: 39-47; 2009.

14. Viti, M.; Mantovani, E.; Babbucci, D.; Tamburelli, C. Plate kinematics and geodynamics in the Central Mediterranean. J. Geodynamics 51: 90-104; 2011.