Bollettino di Geofisica Teorica ed Applicata Vol. 53, n. 1, pp. 89-111; March 2012
DOI 10.4430/bgta0037

Middle term prediction of earthquakes in Italy: some remarks on empirical and deterministic approaches

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(Received: April 29, 2010; accepted: October 1, 2010)

ABSTRACT Recognizing the Italian seismic zones most prone to next strong earthquakes would be quite helpful for a more efficient strategy of defence. So all efforts should be made to understand what chances we actually have of obtaining such information. This work aims at providing information about this problem, by discussing potentialities and limitations of two main types of approach proposed to date: empirical (relying on the hypothesis that the known seismic history provides insights into the behaviour of future earthquakes) and deterministic (based on the presumed knowledge of the tectonophysical mechanisms responsible for the space-time distribution of major events). On the basis of the evidence and arguments presented here**,** we argue that reliable middle term predictions can hardly be obtained by empirical approaches and that the most interesting perspectives can be envisaged for the deterministic approach based on the study and observation of the postseismic relaxation and its possible effects on earthquake probability.

Key words: earthquake prediction, postseismic relaxation, Italy, central Mediterranean.

1. Introduction

From the seismic history of Italy, one major earthquake ($M \geq 5.5$) may be expected to occur within the next decade. If we could manage to know which seismic zones are most prone to such possible event, the defence from earthquakes would be considerably simplified, as the limited economic resources that might be available in the next years could be concentrated in a limited area. Since it is widely accepted that earthquakes are causally related to tectonic processes, the most natural way to get information on where and when a major shock will occur in a given zone would be to study the present tectonic setting and its connection with the space-time distribution of earthquakes in that zone. However, several authors believe that this deterministic approach is not feasible yet, due to insufficient knowledge of the present tectonic setting and the mechanisms that determine when a seismic slip occurs in the most loaded faults. To overcome such presumed difficulties, many researchers have tried to develop an alternative (empirical) strategy that does not need to know the causes of single earthquakes, as it relies mainly on the hypothesis that the known seismic history of the zone involved, analysed under given assumptions, can provide information on future seismic activity.

In this work, we present a different point of view. First, we explain why we think that empirical approaches can hardly provide reliable information on where and when the next earthquakes will occur. Then, we argue that now, in the light of the detailed reconstruction of the present seismotectonic setting in the central Mediterranean region [see Mantovani *et al.* (2009) and references therein] and with the insights into the postseismic relaxation induced by strong decoupling earthquakes in the periAdriatic zones (Mantovani *et al.*, 1997, 2010; Viti *et al.*, 2003, 2004) gained so far, the deterministic approach may enable us to recognize the Italian zones most prone to next major earthquakes.

2. Empirical approaches

We do not aim at entering into the technical details of the various empirical approaches so far proposed in literature [e.g., see Mulargia and Geller (2003) for a comprehensive review]. We only report a critical analysis of the underlying concepts and available data sets.

Considering that the ongoing tectonic processes in the Italian region started in the middle Pleistocene, i.e., around one million years ago [e.g., Piccardi *et al.* (2006) and references therein], the hypothesis that a few centuries of seismic history adequately represents such a long term fracturing pattern, and that consequently it can inform us on location and time pattern of future major events, appears to be mainly speculative. Moreover, the incompleteness of seismic catalogues, for lack of or ambiguous historical information, may result in biased representations of past activity. For instance, this remark is consistent with the fact that the faults activated by the last strongest Italian earthquakes (Irpinia 1980, Colfiorito 1997, San Giuliano di Puglia 2002, L'Aquila 2009) were not previously considered as the most prone in the respective zones (Valensise, 2009).

To make the adopted empirical approach quantitative, a probability model must be defined. In most cases, this requires one or more assumptions about the presumed overall behaviour of seismic activity. The behaviours more frequently considered are the *random distribution of earthquakes in space and time*, *seismic cycle* and *earthquake clustering*. Once one of these models is chosen, the reliability of its predictions crucially depends on whether such a model is consistent with the real seismicity pattern. In the following, we make some considerations about the possible weak points of the above models.

2.1. Random distribution

This hypothesis postulates that earthquakes are independent events. From this point of view, seismic activity can be described in terms of a Poissonian process, whose probability distribution only depends on the mean rate of earthquake occurrence**.** This last parameter is generally inferred from seismicity catalogues, but assembling a data set of presumed independent events requires that foreshocks and aftershocks must be identified and removed from the catalogue, an operation that may involve ambiguities and uncertainties dependent on the definition adopted for such events.

The randomness hypothesis is not compatible with the well recognized fact that earthquakes are causally related with tectonic processes driven by plate motions, which implies that each strong earthquake perturbs the stress and strain fields in the surrounding zones, influencing the space-time distribution of the next major shocks (e.g., Anderson, 1975; Steacy *et al.*, 2005).

2.2. Seismic cycle

This concept implies that earthquake probability is lowest just after a major seismic event and progressively increases up to the occurrence of the next shock. Various versions of this hypothesis have been developed in the form of time predictable, slip predictable and characteristic earthquake models (e.g., Mulargia and Geller, 2003). In particular, the characteristic earthquake model underlies the current seismotectonic zoning of the Italian region, which has involved the recognition of active faults in Italy through the study of the presumed sites of historical earthquakes [DISS, Basili *et al.* (2008)].

If the characteristic earthquake model were plausible, it would provide a very efficient tool for earthquake prediction. However, there are many reasons for believing that such a scheme is oversimplified with respect to reality. In real contexts, the elastic-brittle uppermost crust is characterized by a very large number of fractures created by previous tectonic activity during geological periods, varying in size and orientation. When tectonic stress reaches fault strength, seismic slip develops, activating a number of pre-existing fractures in a cascade process. This phenomenon stops when the fracture propagation encounters major obstacles such as intersecting, branching and bending fractures, where the resistance to sliding overcomes the acting shear stress (e.g., Wesnousky, 2006). This implies that the length and geometry of the seismic fault may considerably vary from one event to the next. This holds as well for the path of the fracture, being the dynamic boundary conditions different from one cycle to the other, depending on the distribution of previous major earthquakes in the surrounding zones. Thus, to assume that the seismic hazard of a zone is controlled by the behaviour of a specific fault seems to be mostly speculative. Moreover, the characteristic earthquake model is mainly based on paleoseismological analyses, which may only detect the faults responsible for major earthquakes [roughly M>5.5 and M>6.0 for normal faults and thrust faults respectively, e.g., Lettis *et al.* (1997) and Pavlides and Caputo (2004)]. This biased fault sampling may improperly support the idea that earthquakes occur at regular intervals along the same fault. Other possible problems of the characteristic earthquake model, related to shortness of historical records, are pointed out by a number of authors (e.g., Stein and Newman, 2004).

The above arguments have led a number of authors to suggest that the characteristic earthquake model is not reliable, in line with the fact that earthquake forecasting based on such a model has been unsuccessful so far (e.g., Mulargia and Geller, 2003; Naylor *et al.*, 2009).

2.3. Clustering

The hypothesis that seismic activity concentrates in time after a major earthquake is largely accepted for aftershocks. As regards major events, instead, the idea that the probability of occurrence significantly increases in the few years following a strong shock is still object of debate. In the Italian area, in particular, such hypothesis is not supported by the distribution of major shocks (M≥6). For instance, since 1600 only 4 (out of 51) major earthquakes occurred within 10 years and 50 km from a previous comparable event. Cinti *et al.* (2004), by modifying the procedure described by Faenza *et al.* (2003), have proposed a procedure for middle term prediction of strong earthquakes (M≥5.5) in Italy. Such an example may be used to make some considerations about the reliability of the underlying approach and the resulting predictions. The main assumption of this method is that the next strong shocks will occur in the zones already hit by major earthquakes. Differently from the approaches described in the previous paragraphs, the probability model adopted by Cinti *et al.* (2004) does not imply any *a priori* choice about seismicity behaviour. However, the procedure requires that several parameters, related to geological and seismological features of the study area, have to be taken into account. Using the set of M≥5.5 earthquakes that occurred in the Italian region from 1600 A.D. to 2003, the above authors conclude that the only parameter that does not have a negligible weight is the rate of earthquake occurrence.

The above methodology was then used to elaborate a prediction map for the Italian territory, tentatively subdivided into 61 seismic zones, presumably characterized by a homogeneous stress regime. Such a map envisages 34 zones with the probability that a M≥5.5 event will occur within 10 years. The results obtained indicate the Friuli zone as the most dangerous in Italy, with a probability of 27%, followed by the southern Apennines (25%), Umbria-Marche (25%), central Calabria (17%), and several other zones with probability lower than 15%, including the central Apennines, where the April 6, 2009 L'Aquila earthquake took place. Insights into the uncertainties that may affect the above prediction map, may be gained by considering the main features of the data sets for all zones (Table 1), as discussed in the following.

- Only 5 zones have more than 5 events. In 25 of the 34 zones considered, the data set is constituted by less than 4 events. In 8 zones, only 1 event is documented.
- In most zones, the interevent times are very scattered, often varying from a few years to more than a 100 years, which reflects a high uncertainty on the estimated occurrence rates.
- The data sets are crucially dependent on the geometry assumed for the zones. Small changes of boundaries may determine strong variations in the data set. For instance, if the central Apennine zone were subdivided into two subzones, corresponding to the major fault systems of L'Aquila and Fucino [tectonically and seismically well distinct, e.g., Piccardi *et al.* (1999) and Pace *et al.* (2002)] the related data sets and the resulting probability would be rather different.
- The presumed homogeneity of the strain regime in the zones adopted is far from being convincing. For instance, zone 8 includes the rather different tectonic pattern of the Mugello (extensional) and Forlivese (transpressional) seismic districts.

Furthermore, it must be considered that the probabilities estimated by Cinti *et al.* (2004) for the various zones are quite similar. For instance, probability only varies by about 10% for the first ten positions of the list. Considering that the uncertainty of such predictions is mostly unknown and presumably very high, as discussed above, one can hardly rely on such small differences to establish priority criteria for practical purposes.

3. Deterministic approach (long range interaction between seismic sources)

This view postulates that major earthquakes are not random in time and space but have some relation to each other, due to the diffusion of stress through the lithosphere (e.g., Elsasser, 1969; Anderson, 1975; Rydelek and Sacks, 1990). The occurrence of a major earthquake at a sector of a plate border triggers a strain perturbation that may significantly increase the probability of earthquakes in the zones where the induced strain changes are most favourably oriented with respect to the geometry of mature faults. Evidence of these processes (controlled by viscoelastic relaxation in the crust-upper mantle system) has been recognized by means of space geodesy, radar interferometry and gravity measurements (e.g., Pollitz *et al.*, 2006; Panet *et al.*, 2007; Ryder

Table 1 - Main features of seismicity data sets of 34 Italian zones given in Table 1 of Cinti *et al.* (2004). *N*=number of $M \geq 5.5$ earthquakes occurred in the period 1600-2003, *T*= average interevent time [404 years/(N+1)], *SD*=standard deviation of interevent times with respect to *T*, T_{min}, T_{max}= minimum and maximum interevent times, *TE*= time elapsed after the last event.

Zone	*N*	*T* (years)	*SD* (years)	T_{min}-T_{max} (years)	*TE* (years)
1	11	33	30	0 - 90	12
2	10	36	29	6 - 88	30
3	10	36	37	4 - 120	13
4	7	50	28	8 - 114	63
5	6	58	43	16 - 129	97
6	5	67	60	0 - 155	64
7	5	67	55	11 - 142	26
8	4	81	50	19 - 127	8
9	4	81	52	79 - 131	20
10	3	101	80	41 - 186	94
11	3	101	116	22 - 254	8
12	3	101	40	61 - 93	229
13	3	101	110	13 - 240	67
14	3	101	58	58 -141	137
15	3	101	66	33 - 154	47
16	3	101	81	32 - 186	32
17	3	101	92	1 - 168	91
18	3	101	63	21 -128	153
19	3	101	91	10 - 196	109
20	3	101	89	8 - 181	93
21	3	101	86	14 - 183	102
22	3	101	104	17 - 227	60
23	3	101	110	6 - 237	90
24	3	101	91	4 - 194	174
25	2				192
26	2				227
27	1				214
28	1				223
29	1				42
30	1				39
31	1				208
32	1				315
33	1				127
34	1				78

et al., 2007).

The analysis of the space-time distribution of earthquakes in various zones suggests that the above phenomenon causes long range (hundreds of km) and long term (years) interaction of seismic sources (e.g., Rydelek and Sacks, 1990, Pollitz *et al.*, 1998; Freed *et al.*, 2007). This interaction has also been recognized in periAdriatic regions (Mantovani *et al.*, 1997, 2010; Viti *et al.*, 2003, 2004; Cenni *et al.*, 2008). A discussion about this last piece of evidence and its possible effects on earthquake probability in Italy greatly benefits from a synthetic description of the information now available on the related tectonic setting, given in the next paragraph.

3.1. Geodynamics and recent/present tectonic context in the central Mediterranean region

The reconstruction of the Neogene evolutionary history of the study area and the analysis of the post-middle Pleistocene deformation pattern, deduced by overwhelming evidence, led us to identify the geodynamic interpretation and present tectonic setting schematically illustrated in Fig. 1 (Mantovani *et al.*, 2009, 2010; Viti *et al.*, 2011). In this view, the ongoing tectonic processes in the central Mediterranean are driven by the relative motions of Africa and the Anatolia-Aegean system with respect to Eurasia. In response to these boundary conditions, the Adria plate, encompassing the main Adriatic continental domain and the northern Ionian oceanic zone, moves roughly north to NNW-ward. The convergence between the Adria plate and the Aegean-Balkan system is accommodated by compressional seismotectonic activity at the boundary zones (e.g., Louvari *et al.*, 2001; Aliaj, 2006).

On the western side of the Adria plate, mainly corresponding to the Apennine belt, the tectonic context is more complex, being conditioned by two main processes. One is the fact that the outer Apennine belt (encompassing the Molise-Sannio units, the eastern sector of the Latium-Abruzzi platform, the Romagna-Marche-Umbria units and the Ligurian units) is carried by the Adria plate and consequently moves faster than the inner part of the belt. The relative motion between these two Apennine sectors is responsible for the extensional-to-transtensional seismotectonic activity in the axial part of the belt, compressional deformation at the outer front of the belt and fast uplift of the mobile belt (e.g., Bartolini *et al.*, 2003; Piccardi *et al.*, 2006; Ascione *et al.*, 2007; Lavecchia *et al.*, 2007). The other process is the outward extrusion of the Calabrian wedge, squeezed by the convergence of the confining plates, at the expense of the Ionian oceanic zone. The relative motion between the Molise-Sannio units, moving in connection with the Adria, and the Calabrian wedge is accommodated by a strike slip deformation at the Lucanian Apennines, where a system of belt-parallel sinistral faults are clearly recognized (e.g., Catalano *et al.*, 2004; Caputo *et al.*, 2008; Ferranti *et al.*, 2009).

3.2. Short-term kinematics

The plate kinematics shown in Fig. 1 relates to the presumed average motion rates since the middle Pleistocene, resulting from a series of short accelerating phases, associated with major coseismic/postseismic phases, and longer interseismic periods, characterized by a much slower motion (e.g., Anderson, 1975; Pollitz, 2003).

Insights into the present kinematic pattern in the central Mediterranean region are provided by geodetic measurements carried out by a network of GPS permanent stations in the central-northern part of the Italian zone (Fig. 2). The fact that the above, short-term pattern is fairly

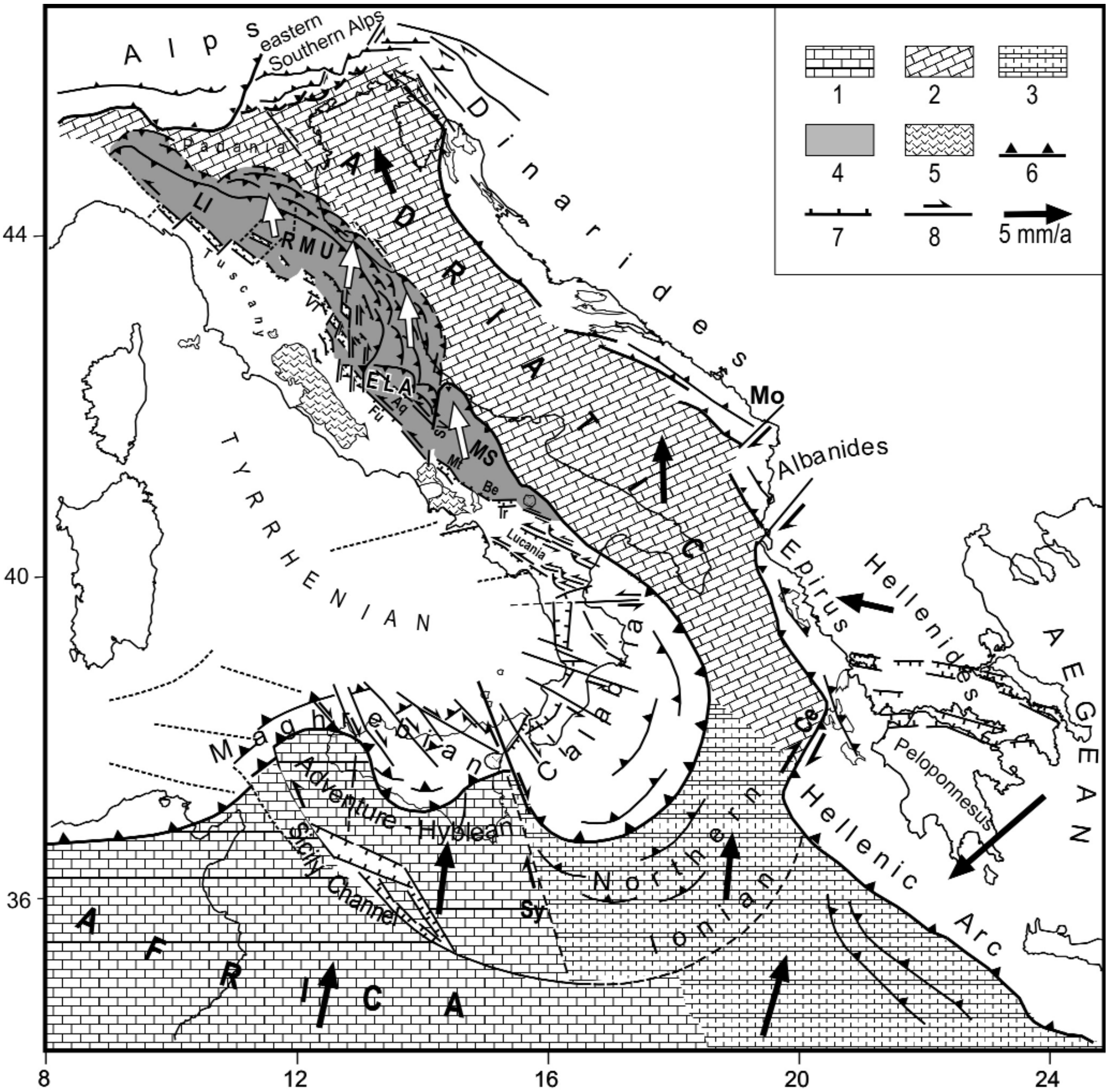

Fig. 1 - Tectonic sketch of the central Mediterranean area evidencing the Apennine wedges (grey) which move faster than the inner belt (see text for comments). Black arrows indicate the kinematics of the African and Adria plates with respect to Eurasia (Mantovani *et al.*, 2007, 2009; Viti *et al.*, 2011). White arrows indicate the kinematics of the Apennine wedges carried by Adria. 1) African continental domain, 2) Adriatic continental domain, 3) Ionian oceanic domain, 4) Apennine orogenic wedges carried by Adria, 5) Quaternary volcanism, 6,7,8) compressional, extensional and transcurrent features. Aq=Aquila transtensional fault system, Be=Benevento normal fault system, Ce=Cephalonia transpressional fault system, ELA =Eastern sector of the Latium-Abruzzi platform, Fu=Fucino transtensional fault system, Ir=Irpinia normal fault system, LI=Ligurian units, Mo=Montenegro, MS=Molise-Sannio units, Mt=Matese normal fault system, RMU=Romagna-Marche-Umbria units, SV=Sangro-Volturno transpressional fault system, Sy=Siracuse escarpment, VT=Val Tiberina trough.

similar to the long-term kinematics deduced by the distribution of post-middle Pleistocene deformation, in particular the faster motion of the outer Apennine belt with respect to the inner Apennines, suggests that at present no significant effects of postseismic relaxation is present in

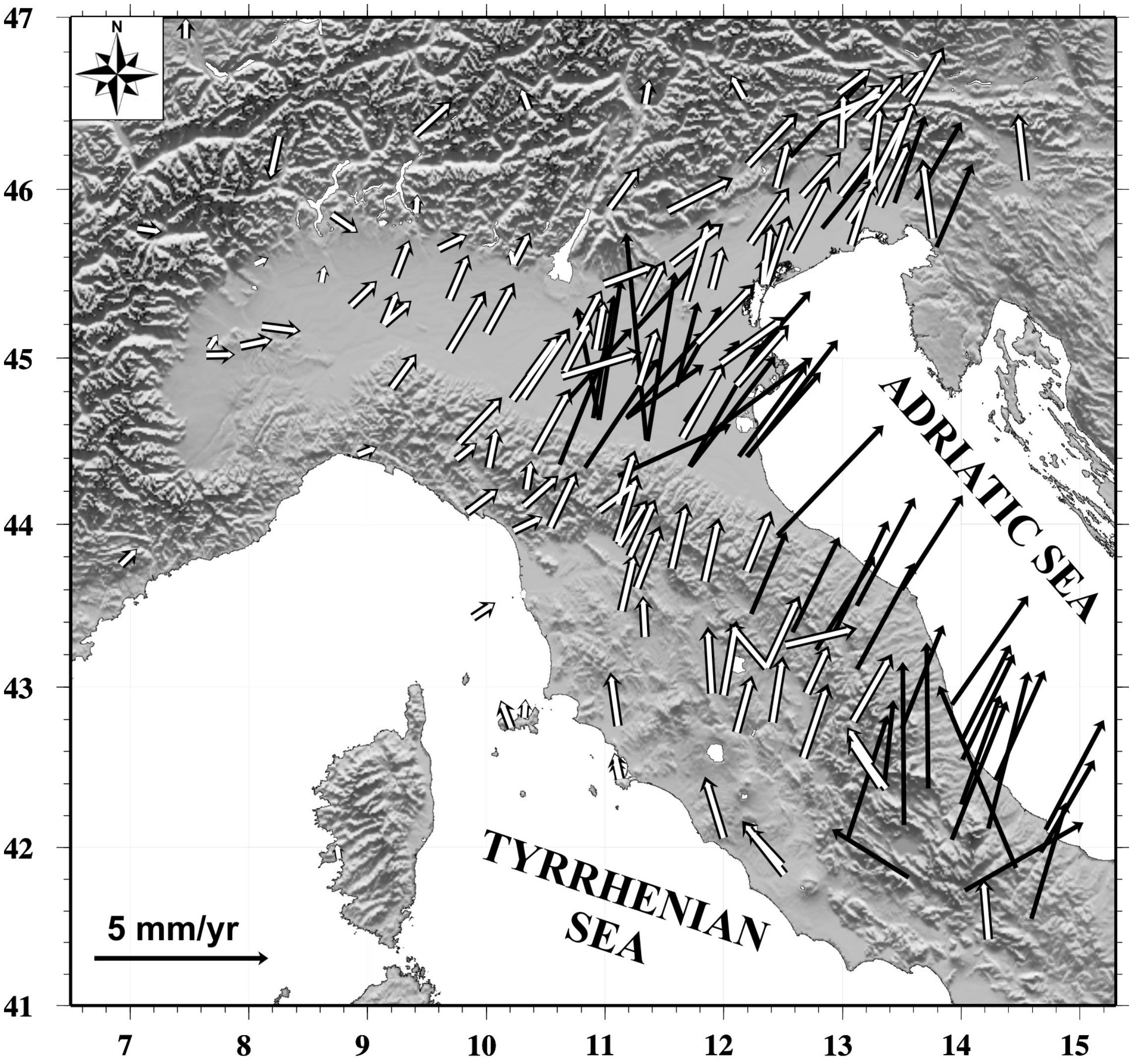

Fig. 2 - Residual velocities, with respect to a fixed Eurasian frame, estimated in central northern Italy by GPS measurements at a network of 202 permanent stations with at least one year of recording. Absolute Eurasia Euler pole at 56.330°N, -95.979°E with rotation velocity ω=0.261°/My (Altamimi *et al.*, 2007). Solid and empty arrows respectively indicate velocities higher and lower than 2.5 mm/y. It can be noted that the zone characterized by the highest velocities fairly corresponds to the outer mobile sector of the Apennine belt evidenced in Fig. 1.

the study area. This may be reasonably associated with the limited amount of major decoupling earthquakes that have occurred in the last decades.

3.3. Long range interaction between southern Dinarides and southern Apennines seismic sources

In view of the tectonic setting shown in Fig. 1, one can reasonably suppose that the decoupling earthquakes that occur at the southern Dinarides thrusting zone (Fig. 3) may favour the seismic activation of belt-parallel normal faults in the southern Apennines (Matese-Benevento-Irpinia

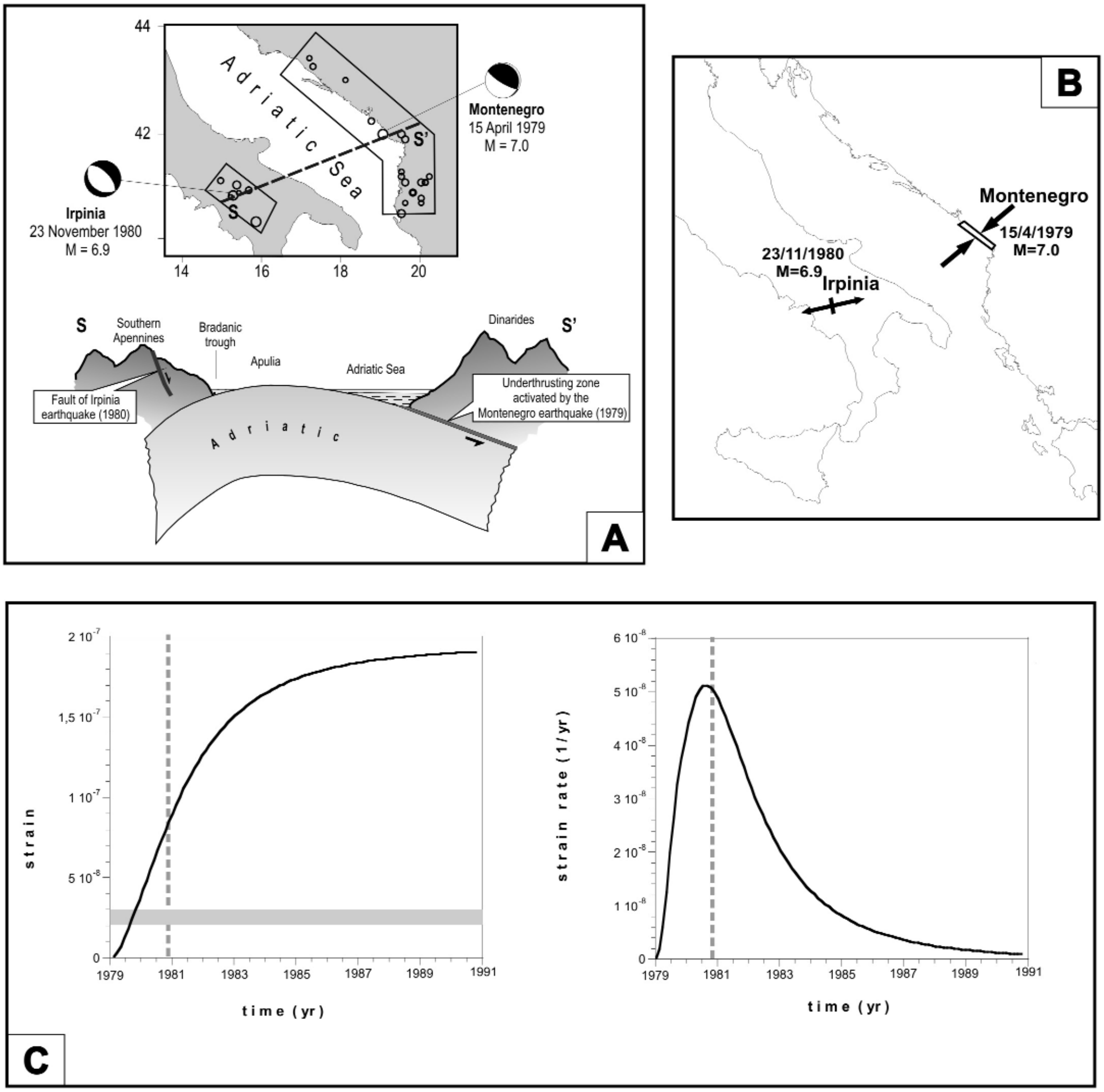

Fig. 3 - Tectonic and seismological evidence about the presumed interrelation between southern Dinaric and southern Apennine seismic sources. a) The map shows the geometry adopted (boxes) for the two interrelated zones and the epicentres (circles) of the major earthquakes that have occurred since 1850 (listed in Table 2). Focal mechanisms refer to the last two strong events (Boore *et al.*, 1981; Giardini, 1993). The cross section (trace SS' in the map) sketches the flexure of the southern Adriatic lithosphere beneath the Apennine and Dinaric belts. b) Modeling of postseismic relaxation induced by the 1979 M=7 Montenegro seismic source (empty bar). The seismic slip is simulated by convergent displacements (arrows) of the fault sides. The value tentatively adopted for such displacement (1 m) derives from Wells and Coppersmith's (1994) scale relationships. The divergent arrows and the perpendicular bar in the Irpinia zone (southern Apennines) indicate the principal axes of the horizontal strain perturbation triggered by the 1979 Montenegro earthquake. c) Computed time patterns of the strain and strain rate induced by the Montenegro event at the Irpinia zone, site of the November, 23 1980 Irpinia earthquake (M=6.9). See Viti *et al.* (2003) for details about the computation methodology. A uniform value (400 m^2s^{-1}) of diffusivity ($D = HhE/\eta$, where H and E are thickness and Young modulus of the upper elastic layer, h and η are thickness and viscosity of the lower viscous layer), is assumed throughout the model. The horizontal grey strip indicates the strain level connected to earth tides, which can be taken as threshold value for earthquake triggering (Viti *et al.*, 2003). The vertical dashed line indicates the occurrence of the 1980 Irpinia earthquake.

Table 2 - List of major earthquakes that have occurred since 1850 in the two zones shown in the map of Fig. 3a. The statistical analysis of these data provides a low value (<10%) of the probability that a major earthquake occurs in the southern Apennines without the occurrence of a Dinaric precursor (see text for comments). Data taken from: Shebalin *et al.* (1974); Papazachos and Comninakis (1982); Postpischl (1985); Comninakis and Papazachos (1986); Papazachos and Papazachou (1997); Ambraseys (1990); Albini (2004); Working Group CPTI (2004); Guidoboni and Comastri (2005).

Southern Apennines ($M \geq 5.5$)	**Southern Dinarides ($M \geq 6.0$)**
1851 (6.3), 1853 (5.9)	1851 (6.1, 6.7, 6.0, 6.1)
1857 (7.0)	1855 (6.5)
	1865 (6.2), 1869 (6.2), 1870 (6.4)
1910 (5.9)	1905 (6.6), 1906 (6.5), 1907 (6.2)
	1923 (6.2)
1930 (6.7)	1926 (6.1), 1927 (6.0)
	1942 (6.0)
1962 (6.2)	1959 (6.0, 6.4), 1962 (6.0)
1980 (6.9)	1979 (7.0, 6.3)

zone in Fig. 1). This hypothesis is consistent with the quantification of the postseismic relaxation triggered by the 1979 M=7.0 Montenegro earthquake in the southern Dinarides (Viti *et al.*, 2003), which predicts a roughly E-W extensional principal axis of strain (Fig. 3b). This prediction may explain why the Montenegro event was followed by the 1980 Irpinia shock (M=6.9) at one of the normal faults of the southern Apennines. Furthermore, the above quantification (Fig. 3c) provides a plausible physical explanation for the observed delays between Dinaric and Apennine events (Viti *et al.*, 2003). Such explanation is based on the hypothesis that earthquake probability is highest when the strain-rate peak induced by the triggering earthquake reaches that zone (e.g., Pollitz *et al.*, 1998; Viti *et al.*, 2003; Cenni *et al.*, 2008). Indeed, experimental studies (e.g., Niemeijer and Spiers, 2007) show that a seismic slip is considerably favoured when faults undergo abrupt strain rate variations. Considering that the southern Apennines is the seismotectonic zone nearest to the triggering Dinaric sources and that postseismic strain perturbation rapidly attenuates with distance, it seems reasonable to expect that the most evident effects of such a phenomenon occur in that zone.

Considerable support to the hypothesis that major earthquakes in the southern Dinarides thrust zone may influence the probability of major shocks in the southern Apennines (Fig. 3) is provided by the fact that other similar time correspondences among major earthquakes have occurred in the last centuries (Mantovani *et al.*, 2010). In particular, because since 1850, all major southern Apennines earthquakes have been preceded, within 4 years, by strong events in the southern Dinarides (Table 2).

The variability of delays between presumed precursors and induced events in such a table may be due to different epicentral locations and depths of the various shocks. Furthermore, it must be considered that earthquake probability in the southern Apennines may increase at least until the induced strain reaches its maximum value. In the example shown in Fig. 3c,

Table 3 - Results of statistical tests, based on Rhoades and Evison's (1979) approach [Eq. (1) in the text], applied to the presumed interrelation between southern Dinarides and southern Apennines (earthquake data sets in Table 2). The considered time interval is 160 years (1850-2010). *PT* = precursory time (the Apennine earthquake is assumed to occur within PT years after the Dinaric event); N_{su} = number of successful predictions; N_{na} = number of failed alarms; N_{fa} = number of false alarms; P_{su} = probability of a successful prediction, P_{fa} = probability of a false alarm, P_{na} = probability of a failed alarm, P_{pr} = probability that an Apenninic event is successfully predicted. See comments in the text. Further details in Mantovani *et al.* (2010).

***PT* (yr)**	N_{su}	N_{na}	N_{fa}	P_{su}	P_{fa}	P_{na}	P_{pr}
3	8	0	8	0.50	0.50	0.10	0.90
4	9	0	8	0.56	0.44	0.09	0.91
5	11	0	5	0.67	0.33	0.08	0.92

strain undergoes a considerable increase for at least 4-5 years after the 1979 triggering earthquake.

To gain insights into the statistical significance of the observed seismic correlation for the period following 1850 (Table 2), Mantovani *et al.* (2010) evaluated the probability through a Monte Carlo procedure, that all seven post-1850 Apennine events occurred by chance within a delay comprised between 3 and 5 years from a Dinaric earthquake. The fact that the resulting probability (ranging between 0.04 and 0.4%) is much lower than the standard threshold value (5%), clearly testifies the statistical significance of the observed correlation.

In order to better understand the practical usefulness of the observed correlation, Mantovani *et al.* (2010) also evaluated the probability of a successful prediction (P_{su}), a false alarm (P_{fa}), a failed alarm (P_{na}) and a predicted event (P_{pr}), by a Bayesian approach (Rhoades and Evison, 1979) which uses the number of successful predictions (N_{su}), false alarms (N_{fa}) and failed alarms ($\mathrm{N_{na}}$):

$$P_{su} = (N_{su}+1)/(N_{su}+N_{fa}+2); \quad P_{fa} = 1\text{-}P_{su}; \quad P_{na} = (N_{na}+1)/(N_{na}+N_{su}+2); \quad P_{pr} = 1\text{-}P_{na} \quad (1)$$

The results of this investigation (Table 3) indicate that a $M \geq 6$ Dinaric event has a probability ranging between 50 and 67% (depending on the considered delay time) of being a precursor of a southern Apennine event. The most interesting result is the low value (8-10%) of the probability that a major earthquake occurs in the southern Apennines not preceded by a Dinaric precursor. From the physical point of view, this result would imply that seismic slip at one of the southern Apennines faults can hardly occur without the decisive contribution of the sudden strain and strain rate increase induced by postseismic relaxation (Viti *et al.*, 2003).

Other time correspondences between Dinaric and Apennine earthquakes can be recognized in the previous centuries (1200 to 1849), as discussed by Mantovani *et al.* (2010). Considering that the magnitude of the strain perturbation induced by strong Dinaric events, as the 1979 Montenegro shock, is significantly higher than the sensitivity of geodetic observations (Viti *et al.*, 2003), the occurrence of a Dinaric event should stimulate the organizing of suitable geodetic surveys or other geophysical observations in the southern Adriatic and Apennine zones, in order to gain further insights into long range interaction of seismic sources in that region.

3.4. Long range interaction between the western Hellenic and Calabrian seismic sources

Another possible example of interrelation between seismic sources involves the two zones shown in Fig. 4, the Calabrian and sestern Hellenic arcs. These zones have been identified by a long series of attempts carried out with various shapes of the zones involved (Mantovani *et al.*, 2008), starting from the idea that seismic activity in Calabria may be favoured by phases of accelerated motion of the northern African margin, triggered by major decoupling earthquakes at its collisional border with the Aegean system. The seismicity patterns of the two zones finally considered (Table 4), suggest that major Calabrian earthquakes (M≥5.5) tend to occur some years after strong shocks (M>6.5) in the Western Hellenic Arc (WHA).

An example of the possible role played by postseismic relaxation in the presumed seismic interrelation is given in Fig. 4, which shows the strain style (Fig. 4b) and time pattern of strain and strain rate (Fig. 4c) predicted in central Calabria as an effect of the 1903 M=8 Hellenic earthquake. The fact that the arrival time of the maximum strain rate is fairly coincident with the occurrence of the strong 1905 Catanzaro earthquake (M=7.1) provides further support to our interpretation. The above earthquake was followed by the famous 1908 Messina earthquake (M=7.2). It is interesting to note that the above two major shocks have probably activated the main lateral guides of the southern Calabrian wedge, i.e., the Calabrian sector that has been characterized by the greatest mobility, and seismotectonic activity, in the recent Quaternary evolution (e.g., Guarnieri, 2006; Del Ben *et al.*, 2008; Finetti, 2008).

The delays between the Calabrian earthquakes and the presumed Hellenic precursors, listed in Table 4, are mostly less than 5 years with very few exceptions. The variability of delays may be due to various factors, such as the location of the precursor and the induced event, the depth of the precursor (most often unknown), the occurrence of more than one precursor, etc. Insights into the possible causes of the above delay range might also be gained by considering the time pattern of strain induced by precursors. In this regard, one has to consider that the probability of earthquakes in Calabria is not only influenced by the value of the strain rate, as discussed earlier, it also depends on the amplitude of the induced strain. For instance, in Fig. 4, it can be noted that after the 1903 event the induced strain in Calabria keeps increasing for about 6 years. The fact that such a time interval is compatible with the range of delays mentioned above is interesting.

The statistical significance of the proposed interrelation, indicated by the fact that the probability that the post-1600 Calabrian events (Table 4) occurred by chance within a delay of less than 11 years from the presumed Hellenic precursors (M>6.5), and computed by the same procedure described in the previous paragraph, is significantly lower than the standard threshold value (5%). We also have tentatively evaluated, through the Rhoades and Evison (1979) approach [Eq. (1)], the probability of a successful prediction and a failed alarm, along with the complementary values: probability of a false alarm and predicted event. The results, given in Table 5, indicate a relatively high probability of a successful prediction (P_{su} = 66-72%) and a very low probability of a non alarm (P_{na} = 13-14%). As we have remarked for the Dinarides-Apennines correlation, this result would imply that seismic slips at the Calabrian faults can hardly occur without the contribution of the strain and strain rate increase induced by strong events in the WHA. An improvement of the above probability values (P_{su} = 80%, P_{na} = 9%) is obtained when the analysis is only carried out for the period 1600-1940, which preceded the effects of the

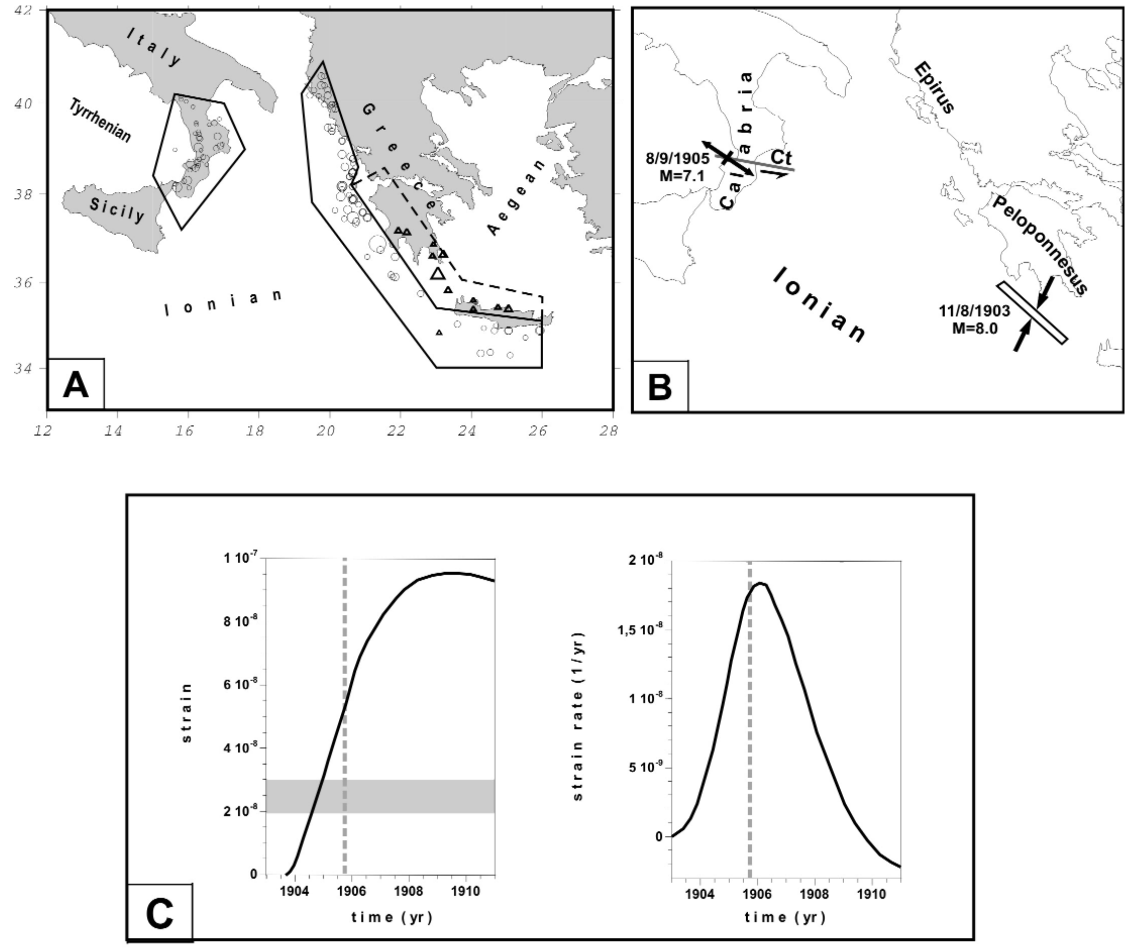

Fig. 4 - Interrelation between western Hellenic and Calabrian seismic sources. a) Geometry (poligons) of the presumably interrelated seismic zones (see text). Circles and triangles indicate the epicentres of shallow (*h*<50) and intermediate earthquakes respectively. The dashed line defines the surface projection of the sector of the Hellenic subduction zone where occurrence of intermediate-depth earthquakes may affect Calabrian seismicity. Seismic catalogues as in caption of Table 4. b) Modeling of postseismic relaxation induced by the 1903 Hellenic seismic source (empty bar). The seismic slip is simulated by convergent displacements (arrows) of the fault sides. The slip value adopted (4.5 m) derives from the Wells and Coppersmith's (1994) scale relationships. The principal axes of the horizontal strain perturbation triggered by the 1903 Hellenic event at the Catanzaro zone (central Calabria) are indicated by the divergent arrows and perpendicular bar [see for details Mantovani *et al.* (2008)]. c) Computed time patterns of the strain and strain rate induced in central Calabria, site of the September 8, 1905 Catanzaro earthquake (M=7.1), by the 1903 Hellenic event. A uniform value (600 m^2s^{-1}) of diffusivity is assumed throughout the model (see caption of Fig. 3). This value, different from that adopted for the case given in Fig. 3, takes into account the fact that the Ionian oceanic domain (where the postseismic perturbation propagates) is characterized by lower heat flow and thicker elastic-brittle layer, with respect to the Adriatic continental domain (Viti *et al.*, 1997). Meaning of the horizontal grey strip as in caption of Fig. 3. The vertical dashed line indicates the occurrence of the 1905 Catanzaro earthquake.

Anatolia-Aegea acceleration, as discussed in the following.

In Table 4, it may be noted that no major earthquakes ($M\geq5.5$) occurred in Calabria for a relatively long period (from 1947 to 1998), notwithstanding the occurrence of a number of possible Hellenic precursors. One could wonder why a seismic zone that for a relatively long time

Table 4 - List of major earthquakes that have occurred since 1600 in the Calabrian Arc and the WHA. The shape of the presumably correlated seismic zones is shown in Fig. 4a. Stars close to magnitude values indicate intermediate-depth earthquakes (h> 50 km). Hellenic events with M>6.5 are in bold. Data taken from: CMT Catalogue (www.globalcmt.org); CATGR1900 (www.geophysics.geol.uoa.gr.); IRIS (www.iris.edu/hq/); Makropoulos and Burton (1981); Sulstarova *et al.* (2000); Working Group CPTI (2004); Galli and Scionti (2006).

Calabria (*M*≥5.5)	**Western Hellenic Arc (*M*>6.0)**
1609 (5.6)	**1601 (6.7)**
1626 (6.1)	**1622 (6.6)**
1638 (7.0, 6.6)	**1629 (7.0*), 1630 (6.9), 1633 (6.9), 1636 (7.2)**
1659 (6.5)	**1655 (6.7)**
	1662 (6.7), 1665 (6.7), 1674 (6.5)
1708 (5.6)	**1701 (6.6)**
	1714 (6.6)
	1723 (6.7)
1743 (5.8), 1744 (6.2)	**1741 (6.7), 1743 (6.9)**
1767 (5.8)	1759 (6.5), **1766 (6.7), 1767 (7.2)**
1777 (5.5)	**1772 (6.7)**, 1773 (6.5)
1783 (6.9, 5.9, 6.6, 5.9, 6.9)	**1780 (7.0)**
1791 (5.9)	**1783 (7.0), 1786 (6.6)**
	1810 (6.5), 1813 (6.4)
1824 (5.5)	**1815** (6.5, **6.6**), **1820 (6.6),** 1823 (6.3)
1831 (5.5), 1832 (6.5), 1835 (5.9)	**1825 (6.8)**
1836 (6.2, 5.8)	**1833 (6.6)**
1854 (6.2)	**1851 (6.6)**
	1854 (6.4), **1858** (**6.7**, 6.4)
1870 (6.2)	**1860 (6.6), 1862** (**6.7**, 6.3, 1865 (6.3), 1866 (6.5, 6.3, 6.3), **1867 (6.6, 7.3)**, 1869 (6.4)
1886 (5.6), 1887 (5.5)	**1885 (6.7*), 1886 (8.2)**
1894 (6.1)	**1893** (6.5, **6.7**, 6.5)
	1895 (6.3, 6.3)
1905 (7.1), 1907 (5.9), 1908 (7.2), 1909 (5.6), 1913 (5.7)	**1897 (7.5), 1899 (6.6*), 1903 (8.0*)**
1917 (5.5)	1908 (6.4*), 1910 (6.2*), 1912 (6.3), 1914 (6.1), 1915 (6.3, 6.5, 6.2)
1928 (5.9), 1932 (5.6)	1919 (6.1), **1926 (7.0*)**, 1927 (6.5*)
1947 (5.7)	1940 (6.1)
	1947 (6.7), 1948 (**6.7, 6.7,** 6.4), **1952 (6.6)**
	1953 (6.3, 6.4), 1958 (6.5), **1959** (6.1, **6.9**), 1962 (6.3), 1965 (6.1)
	1969 (6.2), 1972 (6.4), 1976 (6.3), 1977 (6.2*)
	1983 (**7.0**, 6.2)
1998 (5.7)	1992 (6.5), 1994 (6.4*), **1997** (6.5, **6.6**)
?	2003 (6.2), **2006 (6.7*), 2008 (6.8**, 6.5, 6.2)

Table 5 - Results of statistical tests, based on Rhoades and Evison's (1979) approach [Eq. (1) in the text], applied to the presumed interrelation between the WHA and Calabria (earthquake data sets in Table 4). The considered time interval is 410 years (1600-2010). *PT* = precursory time (the Calabrian earthquake is assumed to occur within PT years after the WHA event); N_{su} = number of successful predictions; N_{na} = number of failed alarms; N_{fa} = number of false alarms; P_{su} = probability of a successful prediction, P_{fa} = probability of a false alarm, P_{na} = probability of a failed alarm, P_{pr} = probability that a Calabrian event is successfully predicted. When a WHA precursor is constituted by two or more events, the length of the alarm time increases correspondingly. When a Calabrian response includes two or more events, we count it as a unique success. The results given in the last row refer to a delay of 10 years and the period 1600-1945. See text for comments.

PT (yr)	N_{su}	N_{na}	N_{fa}	P_{su}	P_{fa}	P_{na}	P_{pr}
5	17	2	10	0.62	0.38	0.14	0.86
8	20	2	7	0.72	0.28	0.13	0.87
10	20	2	7	0.72	0.28	0.13	0.87
10*	19	1	4	0.80	0.20	0.09	0.91

interval (1600-1946) was characterized by an average recurrence time of 17 years for $M \geq 5.5$ earthquakes had been silent then for more than 50 years, and why a fairly regular (Table 5) and long (more than 350 years) interrelation between Hellenic and Calabrian events was not fulfilled during the above period. A possible explanation for such "anomalous" behaviour could be found considering that the above quiescence just followed an exceptional tectonic event, i.e., the strong acceleration that the westward migration of the Anatolian-Aegean system underwent in response to the seismic activation (involving several meters of coseismic displacements for each major earthquake) of the entire North Anatolian Fault system since 1939 (e.g., Barka, 1996; Cenni *et al.*, 2002). Such a forward jump of the Anatolian-Aegean extruding system might have increased resistance at the WHA subduction fault, with consequent slow down of the motion of the African domain facing that arc. This hypothesis might explain why intermediate seismic activity beneath the WHA, presumably related to the subduction of the northern African margin, underwent a considerable attenuation after 1945 and why, almost simultaneously, shallow seismicity at that arc and at the main tectonic zones surrounding the Aegean block (presumably related to the overthrusting of that wedge on the descending African lithosphere) considerably increased (Figs. 5a, 5b, 5c). In this regard, one could note that the major Hellenic earthquakes that occurred during the seismic quiescence of Calabria (Table 4), mainly occurred at the collisional border between the Peloponnesus wedge and the southern Adriatic domain (Cephalonia fault, in particular). The slowdown of the African northern margin in the central Mediterranean zone might be responsible for the reduced seismic activity of Calabria after 1947, being the deformation of the Calabrian wedge mainly driven by the motion of the adjacent African domain (Mantovani *et al.*, 2009; Viti *et al.*, 2011).

In this view, one would expect that seismic activity in Calabria will again be sensible to WHA precursors when they are related to the subduction of the northern African margin. One may expect that such a situation will be pointed out by the strengthening of intermediate-depth seismicity beneath the WHA. The occurrence of $M \geq 5.5$ earthquakes in Calabria in 1998 and 2001 and the fact that such events were preceded (1997) by possible precursors in the WHA (Table 4) could indicate that the mechanism responsible for the proposed interrelation is reactivating.

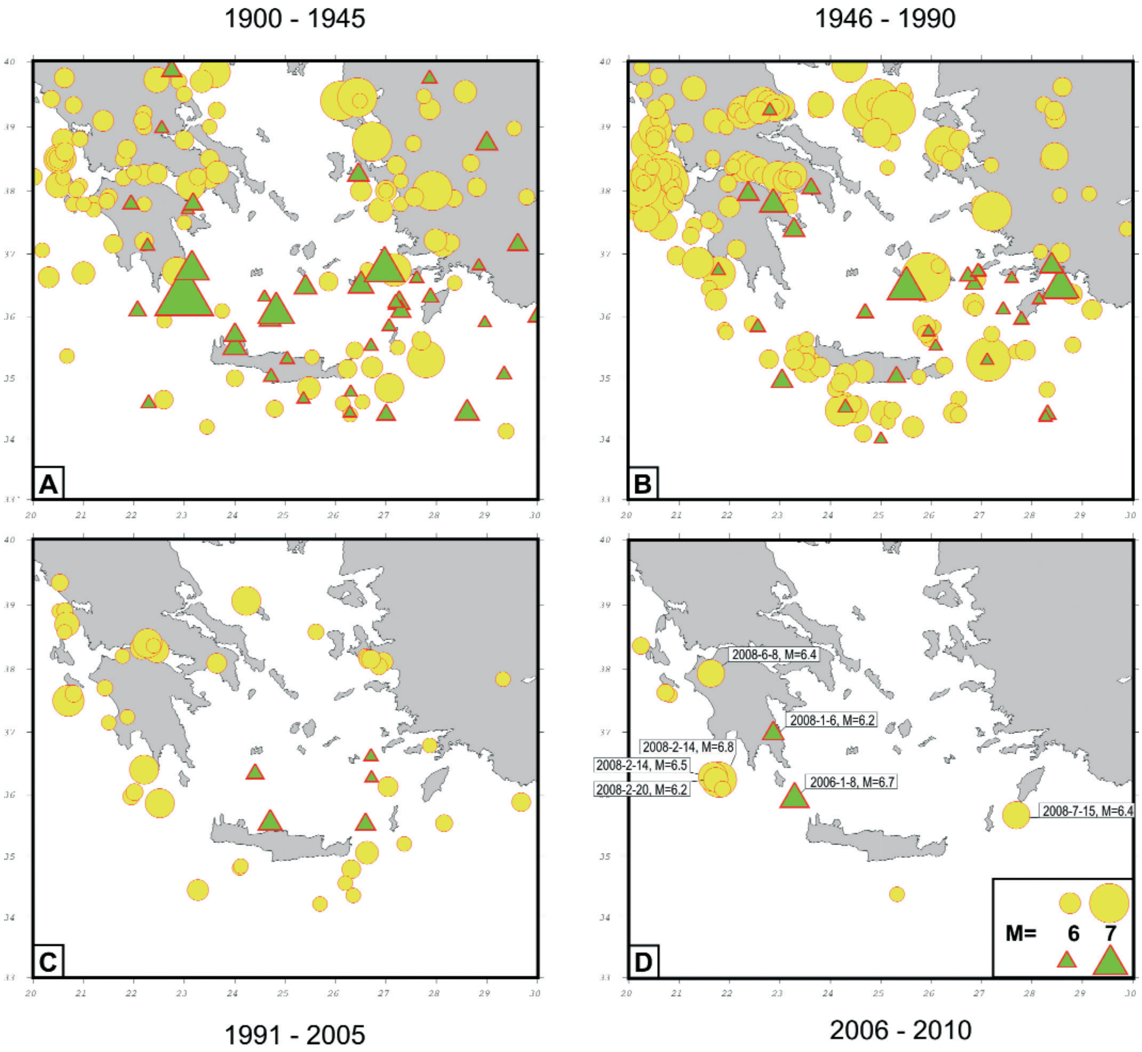

Fig. 5 - Distribution of major earthquakes ($M \geq 5.5$) in the Aegean zone since 1900. a) The first phase precedes the presumed effects of the activaction of the North Anatolian Fault, which involved 4 major earthquakes ($M \geq 7.1$) that occurred from 1939 to 1944 (e.g., Barka, 1996). b) In the second phase, a relative decrease of intermediate-depth seismicity along the WHA and an increase of shallow seismicity at the same arc and the other major tectonic boundaries of the Aegean wedge can be noted. c) In the third phase, seismicity decreases further d) The fourth, most recent phase is characterized by the occurrence of some new major intermediate-depth earthquake beneath the WHA.

Insights into this hypothesis might be gained by geodetic monitoring of the effects of postseismic relaxation triggered by the recent intermediate-depth earthquakes beneath the WHA (Fig. 5d), which, on the basis of the pre-1947 seismic histories (Table 4), could be recognized as possible precursors of Calabrian events.

3.5. Space-time distribution of major earthquakes and tectonic setting in the Apennine belt

The proposed tectonic context in the central Mediterranean region, the Apennine belt in particular (Fig. 1), may provide plausible explanations for the space-time distribution of the

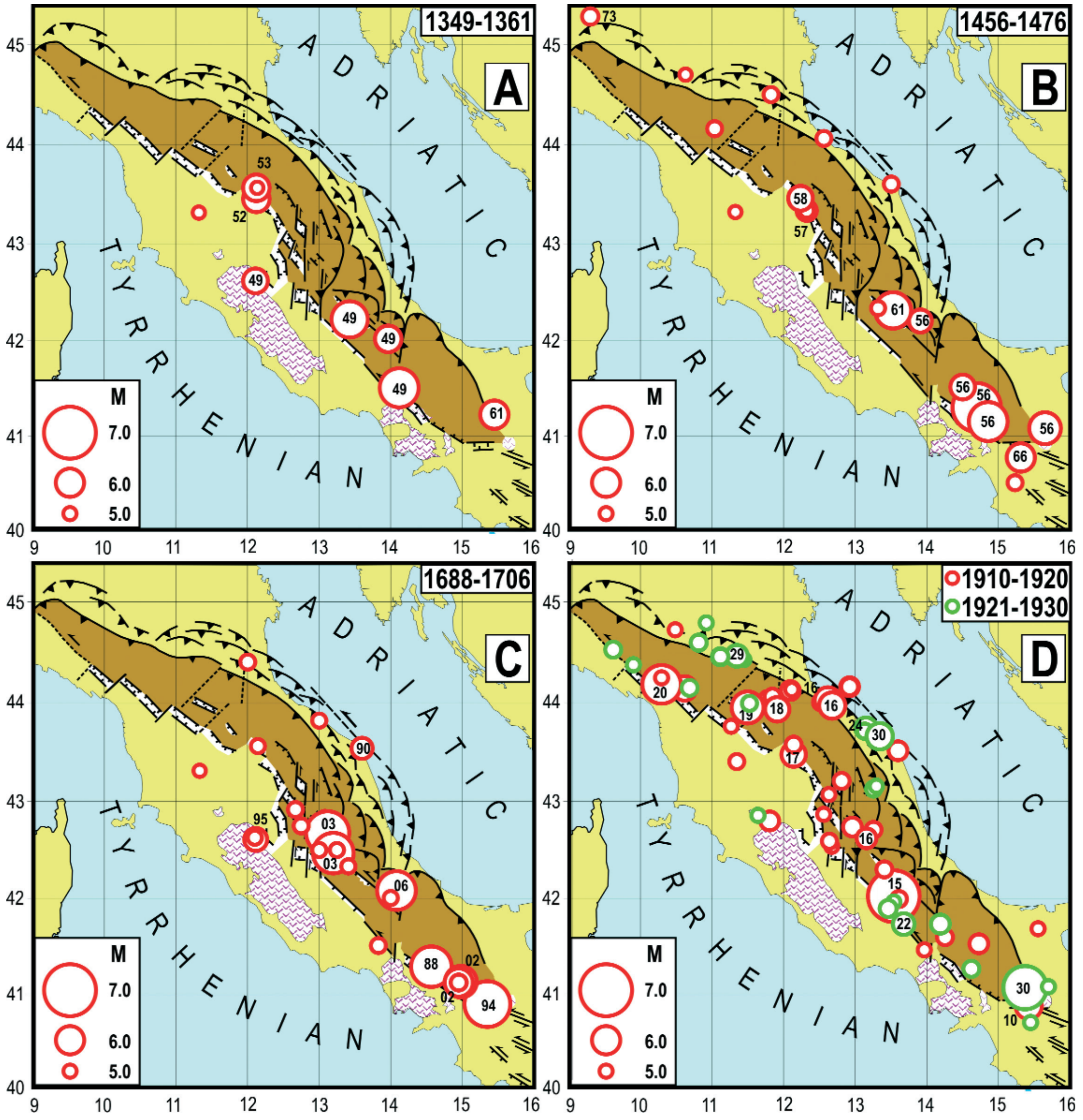

Fig. 6 - Distribution of major earthquakes ($M \geq 5.0$) in the Apennine belt during the last most intense seismic phases. See text for comments. Numbers inside or close to largest circles ($M \geq 5.5$) indicate the year of occurrence. Data taken from Postpischl (1985), Working Group CPTI (2004) and Guidoboni and Comastri (2005). Tectonic scheme and symbols as in Fig. 1.

strongest historical earthquakes that have struck the Italian peninsula since 1300 (Fig. 6). The first seismic sequence (Fig. 6a) started in 1349 with a strong earthquake (M=6.6) at the inner extensional border of the Molise Sannio (MS) wedge. After that decoupling event, the motion of the MS wedge, driven by the Adria plate, may have accelerated, emphasizing its belt-parallel push on the eastern part of the Latium-Abruzzi (LA) platform (Fig. 1). Such dynamics emphasized sinistral shear at the two main transtensional fault systems (L'Aquila and Fucino) which accommodate decoupling between the eastern and western sectors of LA (Mantovani *et al.*, 2010). This could explain why a strong earthquake (1349, *M*=6.5) also occurred at the L'Aquila fault system. In turn, such decoupling accelerated the eastern LA sector, enhancing its push on the Romagna-Marche-Umbria (RMU) units in the northern Apennines. This could explain why seismic activity increased at the inner border of the RMU wedge (Fig. 6a), particularly in the northern Valtiberina trough (1352 *M*=6; 1353 *M*=6; 1358 *M*=5).

The second sequence of strong earthquakes started in 1456, at the southern Apennines, where three almost simultaneous strong decoupling earthquakes (1456, *M*=7, 6.6, 6.3) struck the internal extensional border of MS (Fig. 6b). As in the previous case, the acceleration of the MS wedge might have emphasized shear stress in the axial part of the LA platform, where, in fact, strong shocks occurred at the L'Aquila fault zone in the same year (1456, *M*=5.8) and some years later (1461, *M*=6.5). The consequent increase of tectonic load on the RMU units, due to the acceleration of the eastern LA, might be responsible for the occurrence of earthquakes along the internal and external borders of that wedge (1456 *M*=5; 1457 *M*=5.6; 1458 *M*=5.9).

The third sequence started at the inner border of the MS wedge with the 1688 (*M*=6.7) earthquake (Fig. 6c). Other seismic decouplings at the same extensional boundary occurred in 1694 (*M*=6.9) and 1702 (*M*=6.3). The consequent stress increase at the axial zone of the LA platform might be responsible for the occurrence of two strong events in 1703 (*M*=6.8 and 6.7) at the L'Aquila decoupling fault system, which ruptured up to the Umbria-Marche Apennines (Cello *et al.*, 1998), and of the 1706 major event (*M*=6.6) in the southernmost sector of the same fault system (Maiella zone).

The fourth and most recent seismic sequence (Fig. 6d) started in 1910 with an intermediate earthquake at the southern Apennines (*M*=5.9). This event was followed by a strong earthquake (1915, *M*=7) at the Fucino fault systems. The influence of this last decoupling shock on the tectonic instability of the northern Apennines, with the mechanism discussed earlier, is clearly suggested by the fact that in the period following the Fucino event most seismic zones lying at the inner and outer borders of the RMU and Ligurian wedges were activated by earthquakes of *M*>5.5 (Fig. 6d). Such an exceptional time concentration of major shocks in the northern Apennines (6 events in the 1916-1920 period) is considerably anomalous with respect to the known seismic history of these zones. The fact that such an earthquake storm occurred just after the 1915 Fucino decoupling event, which is presumed to increase tectonic load on the northern Apennines (Viti *et al.*, 2004) can hardly be taken as casual.

The possible role of post-seismic relaxation in the above seismic sequence is suggested by the space-time distribution of earthquakes (characterized by delay times increasing with distances) and by the quantification of the effects of such phenomenon (Cenni *et al.*, 2008).

The fact that the seismic response of the northern Apennines following the 1915 Avezzano earthquake was much more intense than in the other cases given in Fig. 6, may be tentatively explained by the following interpretation. When a seismic slip occurs at the more external L'Aquila fault, the decoupled ELA wedge is relatively narrow, and thus mainly stresses the outermost sector of the RMU, as occurred in the three cases shown in Figs. 6a, 6b and 6c. When, instead, seismic decoupling develops at the more internal Fucino fault system, as occurred in 1915 with the Avezzano earthquake, the sector of ELA which accelerates is significantly wider and consequently stresses the whole RMU wedge in the northern Apennines, emphazising the seismic effects of such perturbation in the seismic zones of the northern Apennines.

4. Conclusions and discussion

Reliable information about which Italian seismic zones are or will be prone to strong shocks within a few years could be very helpful for the Civil Defence Department. We argue that such information may be obtained by the deterministic approach that exploits the detailed knowledge of the present tectonic setting in the central Mediterranean region and the information so far acquired about postseismic relaxation and its possible effects on earthquake probability in the Italian zones. Our confidence in that approach is supported by the fairly good agreement between the space-time distribution of strong historical earthquakes in some Italian zones and the effects predicted by our tectonophysical interpretational scheme. For instance, the present knowledge on the tectonic setting of the southern Adriatic region, the quantification of postseismic relaxation and the time space distribution of historical earthquakes in that zone suggest that the occurrence of a major earthquake ($M \geq 6$) in the southern Dinarides may significantly influence the probability of $M \geq 5.5$ events in the southern Apennines. Statistical analysis of the post-1850 seismic histories of the presumably interrelated seismic zones (Fig. 3 and Table 2) indicates that a $M \geq 5.5$ earthquake in the southern Apennines has a fairly low probability of occurring (less than 10 %) when no $M \geq 6$ events have occurred in the southern Dinarides during the previous 5 years. This would imply that earthquake probability is presently low in the southern Apennines, given that the last strong earthquake in the southern Dinarides occurred in 1979. The probability of an $M \geq 5.5$ event would considerably rise (>50%) in the southern Apennines in the case of a $M \geq 6$ event occurring in the Southern Dinarides. The uncertainty that may affect the above predictions depends mainly on the limitation of the correlated seismic histories. Some remarks about this problem are given by Mantovani *et al.* (2010).

Another significant seismic interrelation is recognized between the WHA and Calabria (Fig. 4 and Table 4). In this case, the observed interrelation refers to a longer period (from 1600 to 1945). The fact that from 1948 to 1997 no $M \geq 5.5$ earthquakes have occurred in Calabria, notwithstanding that some possible precursors did occur in the WHA, could attenuate our confidence in the presumed interrelation. However, we think that the above peculiar seismic quiescence of Calabria and the related interruption of a fairly regular interrelation that has lasted for about 350 years could be an effect of the westward acceleration that the Anatolian-Aegean system has undergone since 1939 in response to the seismic activation of the entire North Anatolian Fault. In admitting that the above interpretation is reliable, the problem of recognizing whether such an exceptional context and its influence on the presumed interrelation, is still going on, remains. For instance, the fact that the 1997 Hellenic precursor (M=6.6) was followed by the 1998 Calabrian shock (M=5.6) could imply that the tectonic mechanism underlying the presumed correlation is again active. The plausibility of this hypothesis could be tested by monitoring the seismic behaviour of Calabria after the occurrence in 2006 and 2008 of major earthquakes in the WHA (Fig. 5d).

The regularities recognized in the time-space distribution of major historical earthquakes in the Apennine belt (Fig. 6), considered in the light of the present tectonic setting (Fig. 1), might provide insights into the probability of the next major earthquakes occurring in the central and northern Apennines. The main tentative hypotheses suggested by the above evidence can be synthesized as follows.

- Next major decoupling earthquakes in the southern Apennines will favour the acceleration of the Molise-Sannio wedge. This is expected to emphasize shear stress at the transtensional fault systems of the central Apennines, increasing the probability of earthquakes. When major decoupling events occur in these last zones, the consequent acceleration of the eastern Latium-Abruzzi platform emphasizes stress (and earthquake probability) along the inner and outer boundaries of the Romagna-Marche-Umbria and possibly the Ligurides wedges.
- The seismic effects of these tectonic mechanisms were fairly evident when very intense decoupling earthquakes triggered the movements of the various sectors of the outer mobile Apennine belt (Fig. 6). This finds a plausible mechanical justification in the fact that seismic slip is favoured by the strain rate increase triggered by strong shocks (e.g., Niemeijer and Spiers, 2007). Instead, we have less information on how seismic activity in the central and northern Apennines is influenced by single earthquakes, even strong ones at the southern Apennine decoupling faults, such as the 1980 M=6.9 shock that struck the Irpinia zone. Preliminary results from numerical modelling (like the ones described in Figs. 3 and 4) suggest that the time pattern of the post-seismic strain perturbation induced by the 1980 Irpinia shock could be compatible with the occurrence of the 1984 Val di Sangro (southern Abruzzi) earthquake (M=5.9).

We are obviously aware that the information provided by the deterministic approach discussed in this work should be used with caution, due to the underlying uncertainties. However, we think that the evidence and arguments described in this work delineate a powerful tool for middle term earthquake prediction in Italy. We do not believe, instead, that similar interesting perspectives can be envisaged for the empirical approaches so far proposed. Above all, we think that a seismic history some centuries long can hardly be taken as representative of a much longer (at least 1 My) history of seismic faulting. This consideration is consistent with what has happened in the last decades in Italy.

Notwithstanding the above difficulties, an empirical method is currently used to compute earthquake probability maps for the Italian territory, aimed at informing the Civil Defence Department. However, the analysis of the main underlying concepts and data sets points out that the resulting predictions may be affected by very high uncertainty, implying that recognizing the Italian zones most prone to the next strong earthquakes can hardly be achieved by this kind of approach.

Acknowledgments. We thank two anonymous referees, whose comments have helped us to improve our paper. This research was financially supported by the Ministero dell'Istruzione, Agenzia Spaziale Italiana and Regione Toscana.

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