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SEISMICAL HAZARD: SEISMOTECTONIC APPROACH

RISQUES SISMIQUES: APPROCHE SISMO-TECTONIQUE

SUMMARY

Reliable seismotectonic models can usefully integrate statistical analyses for evaluating seismic hazard. Unfortunately, no scientific methodology is as yet available for elaborating univocal seismotectonic models in orogenic areas. Methodological problems and the state of the art on the subject are briefly discussed in this paper. The results of a seismotectonic analysis of Italy are also presented. These results show an interesting case of coexistence, at short distances, of different earthquake-generating stress-fields related to different geodynamic processes.

RESUME

Les modèles sismotectoniques intégrer utilement l'analyse statistique pour une meilleure évaluation du risque sismique. Jusqu'à présent, il n'y pas de methodologies scientifiques pour l'élaboration des modèles sismotectoniques valides pour toute les régions orogeniques. Cette note présente et discute les problémes méthodologiques et l'état actuel de connaissance. Les résultats obtenus sur l'Italie montrent comme dans une petite aire, on peut avoir trés differentes contraintes, produites par différentes conditions géodynamiques, qui sont responsables des tremblements de terre.

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The major goals of seismotectonics are the recognition and location of the seismogenetic structures; the evaluation of their seismic potential, the prognosis of the focal parameters for the expected medium and high-magnitude earthquakes. A seismotectonic model, therefore, should allow us to interpret in a coherent way the regional seismicity, to indicate where future events will occur, to prognosticate which type of earthquake (depth, maximal magnitude, focal mechanism) may be expected for every part of the seismogenetic structures. It appears obvious that such a reliable seismotectonic model might usefully integrate the statistical analysis of the historical and present-day seismicity in order to evaluate the seismic hazard. In extreme cases, where adequate earthquake catalogues are missing, the seismotectonic analysis would be the only correct instrument to evaluate the seismic potential of a particular region.

Methodologies on which correct seismotectonic analyses may be based have been proposed by several authors. Criteria for recognizing seismogenetic structures and evaluating their seismic potential by analysis of the surface faulting have been indicated by ALLEN (1976). These criteria appear to be successful in some regions ot the world, but are inadequate for the Mediterranean region where a very complex kinematic pattern is recognizable, generated by different geodynamic processes coexisting within relatively small areas. In the Apennines, moreover, the occurrence of widespread plastic nappes often prevents direct correlations between exposed tectonic features and deep-seated, earthquake-generating, structures. Finally, the seismotectonic analysis of this area appears even more complicated by the fact that many faults which have been recognized as strongly active during the Late Pliocene and the Early Quaternary appear to be silent in historical times. Typical examples are major longitudinal faults which during the early Pleistocene dissected the Tyrrhenian margin of the mountain chain (see, e.g. the large founderings in the Lazium volcanic region and in the Campania Plain), as well as some major transverse faults which cut across the whole mountain system (e.g. faults bordering the Sibari Plain to the North). The amount of vertical displacement across these discontinuities often exceeds three thousand metres, but no significant historical earthquake related to these structures is recorded in the Italian catalogue. Strong earthquakes, on the other hand, have occurred in areas characterized by the absence of important faults at the surface (see, e.g., Irpinia 1930 earthquake).

Semi-quantitative methods for recognizing earthquake source-areas in orogenic regions and for evaluating the seismic potential of the relative active structures have been elaborated by Soviet scientists, following two different approaches (BUNE et al., 1974; GELFAND et al., 1972).

The first methodology, exhaustively described in BORISOV et al., (1976), attempts the prognosis of the maximal expected magnitudes in a certain region firstly by the individuation of geological (e.g. amount of recent vertical movements, length of fault lines) and geophysical parameters (e.g. horizontal gradient of the isostatic anomalies) which have been considered significant for the seismogenesis, secondly by the settlement of the weights for the single parameters and finally by the formalization of the function which defines the expected magnitude. The method, calibrated in the Caucasus mountain system, was applied to Northern Italy (BORISOF et al., 1977) immediately after the descructive 1976 Friuli earthquake. In fact, Friuli resulted in the experiment as a dangerous area, so that the attempt was judged succesful. Nevertheless, our opinion is quite different, since active structures which have released destructive earthquakes in historical time (e.g. buried Ferrara Folds) have not been recognized as dangerous by the method, while area with very low seismicity (e.g. Ivrea zone, Central Alps) have been recognized as source-zones for high-magnitude earthquakes. These discrepancies derive, in our opinion, from the basic postulates which guided the seismogenetic-process interpretation and consequently, from the selected parameters which have been considered as significant for ther seismic-potential evaluation; therefore, they cannot be removed simply by improving the analytical data. The attempt to elaborate a semi-quantitative method which considers every seismic event as a product of evaluable concurrent parameters represents, in any case, a very important step in the investigation addressed to the individuation of the seismogenetic structures and to the prognosis of the maximal expected magnitude in earthquake-prone areas.

The second methodology, well described in GELFAND et al. (1972), attempts the individuation of dangerous areas by using simple geological-morphological parameters (lineaments, elevations etc.) and quite sophisticated pattern-recognition techniques. This method, calibrated in the Caucasus region, has been applied to disparate seismic areas of the world (see GELFAND et al., 1976) and was also tested in the Italian region in 1980 (CAPUTO et al., 1980). The main result of the experiment in this region was a close correlation between high elevations and dangerous intersections, suggesting dominant dip-slip motions in the neotectonic evolution of the Italian area. Both method and results require some basic comments. The postulate that strong earthquakes must occur in correspondence to «disjunctive knots» is highly questionable; in the method, however, this assumption heavily conditioned the results. A rough and acritical choice of the geological-morphological parameters, moreover, may further reduce the reliability of the results, as in the Italian experiments. In spite of our lack of confidence, we believe that important advances may be obtained through pattern-recognition techniques by selecting more significant geological and geophysical parameters. For instance, some improvements of the method have been furnished by French adn Soviet scientists who recently tested the seimiscity of the Western Alps (CISTERNAS et al., 1985).

In recent years, several attempts have been made in Italy to find significant correlations between main geophysical features and earthquakes (PANZA et al., 1981; CASSINIS et al., 1984), as well as between crustal structures and neotectonic behaviour on the one hand and seismicity on the other (see, e.g., BARBANO et al., 1978; DE VIVO et al., 1979; EVA et al., 1978; GASPARINI and PRATURLON, 1981; GASPARINI et al., 1982; LAVECCHIA and PIALLI, 1982; GHISETTI and VEZZANI, 1982; CATTANEO et al., 1983; SLEJKO et al., 1986; CIARANFI et al., CAVALLIN et al., 1984; BOCCALETTI et al., 1985; CAPPONI et al., 1980; GHISETTI et al., 1982). A preliminary seismotectonic map of the whole country, moreover, was elaborated in 1982 (GRUPPO REDAZIONALE etc., 1982). This interdisciplinary approach certainly produced some remarkable results and favoured, on the whole, considerable improvements in the seimotectonic investigation. We must admit, however, that a satisfactory methodology for elaborating reliable seismotectonic models in complex orogenic areas is still lacking.

In this paper we do not aim to propose a definite seismotectonic model of the Italian region. For the previously expressed reasons, we consider the present state of the art still inadequate to reach such an objective. We actually intend to discuss some new results in the seismotectonic investigation which appear rather promising, and which derive from a kinematic approach to the problem. The kinematic analysis was carried out in order to evalute the present trend of tectonic activity in every geological sector of the Italian region, as well as in order to investigate the mutual relationships between the major tectonic structures. The kinematic approach, in fact, permits the reconstruction of sufficiently large trend-intervals of the functions which describe against time and space the values of parameters indicative of the tectonic activity within the investigated region (e.g. subsidence or uplift rates, motions along extensional, compressional and trascurrent features etc.). This approach may consequently allow us to better constrain the extremes of these curves at the time zero, that is, to better control the points which describe the present-day tectonic activity. Moreover, a careful kinematic analysis is the only correct instrument for describing the spatial distribution of the main active structures, for recognizing types and amounts of motion at the boundaries of the single kinematic blocks, and for reconstructing local and regional stress-fields by the available structural and seismological data.

The time interval we chose for the kinematic analysis ranges from the uppermost Miocene to the Present. This choice was determined by three main considerations: Pliocene-Quaternary tectonics was responsible for very large and widespread modifications in the crust-mantle and in the lithosphere-asthenosphere systems in the whole region; the time span is sufficiently long to give a satisfactory picture of the tectonic-activity trend; and the resolution of the kinematic analysis is fairly good in this interval. Previous tectonic activity has also been taken into account, but only to fix some boundary conditions. Our analysis is inadequate for a careful reconstruction of the tectonic evolution after Middle Pleistocene times. We postulated (and this is an unproved basic assumption) that the general trend of the tectonic activity, as well as the pattern of the regional stress-field, has not drastically changed in the last half million years. Drastic changes in the tectonic activity, in fact, would be revealed by drastic changes in the morphotectonic evolution whereas no relevant anomaly has been recognized with respect to the evolution predicted by the general kinematic model.

Fig. 1 shows the first-order structural elements of the investigated region. The Po-Adriatic-Ionian area, representing the foreland of the Calabrian Arc, Apennines, Southern Alps and Dinarides-Hellenides, is constituted, at least in the Po-Adriatic part (but probably also in the Ionian Sea, see FARRUGIA and PANZA, 1981), by a rigid continental litosphere whose margins were larlely consumed during the Tertiary compression. The main recent deformational features in this area are represented by WNW-ESE trending faults which have probable dextral strike-slip displacements. Intermediate and deep-focus earthquakes in the Southern Tyrrhenian Sea indicate a sinking of the Ionian lithosphere beneath the Calabrian Arc. The Tyrrhenian Sea is a young oceantype basin (SCANDONE, 1979; SARTORI and SCANDONE, 1985) which opened and spread mainly during latemost Miocene and Pliocene times. Recent extensional features related to the late evolution of the Tyrrhenian basin are widepread along the Northern-Apennine and the Calabrian Arc inner margins. From the Po Plain to the Calabrian Arc, the outer margin of the mountain chain, as well as the inner margin of the adjacent foredeep system, is characterized by severe compressional features, with a considerable amount of orogenic transport during Pliocene and Pleistocene times (Pieri and Groppi, 1981; Castellarin et al., 1985; Mostardini, 1986; Barone et al., 1982). The compressional fronts of the Southern Alps, on the countrary, appear inactive since latemost

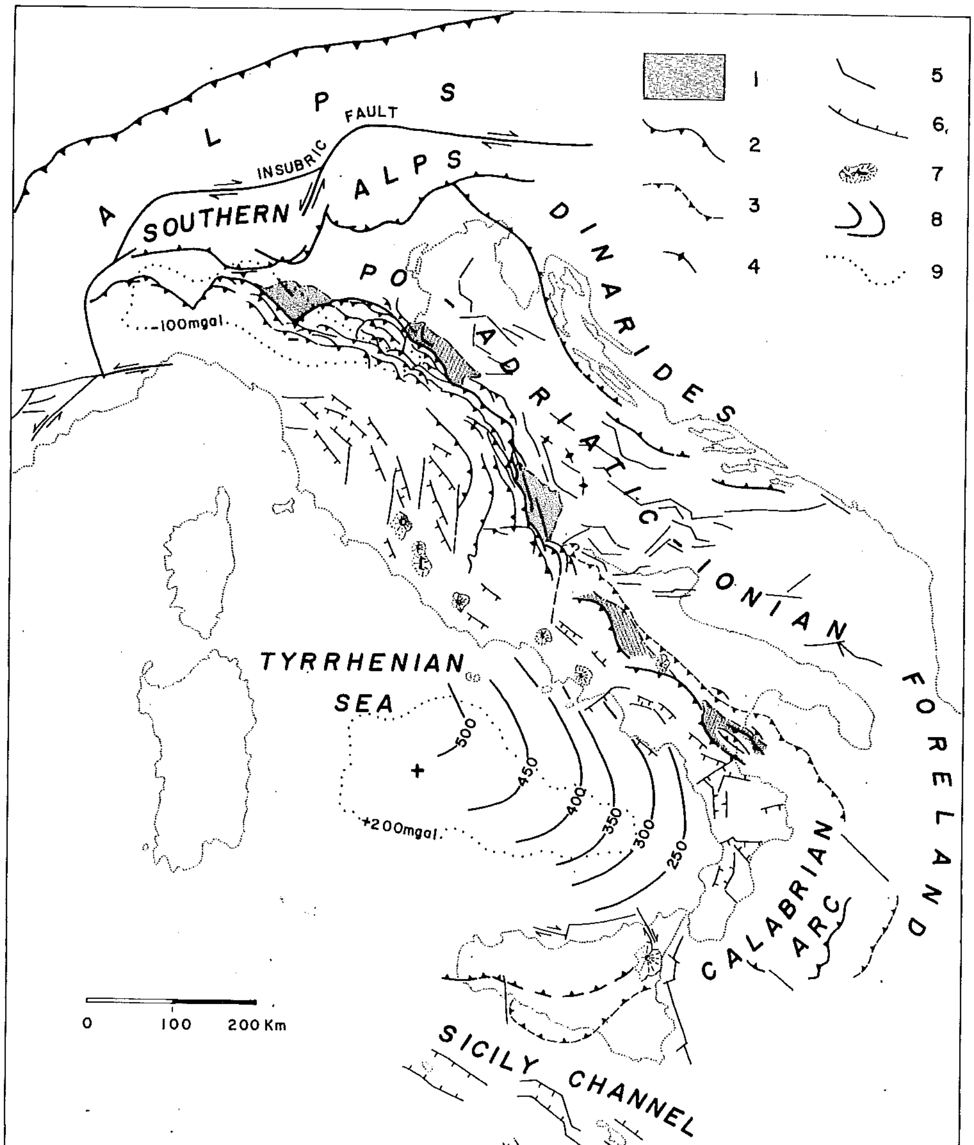

Fig. 1 – Major structural elements of the Italian Peninsula and surrounding areas; 1) Foredeep basinal areas where Pliocene-Quaternary deposits overlying the Po-Adriatic crust exceed 4.000 metres in thickness; 2) Major overthrusts in the Apennines; compression fronts in the Alps, Southern Alps and Dinarides; 3) Front of the « plastic nappes » in the southern Apenninic arc; 4) Upper Pliocene-Quaternary folds in the Adriatic foreland; 5) Faults (mainly strike-slip faults); 6) Normal faults; 7) Quaternary subaerial volcanoes; 8) Isobaths of the subducted Ionian lithosphere; Maximal (positive and negative) Bouguer gravity anomalies.

Miocene times, except in the eastern sector, from the Garda Lake to the Western Dinarides, where evidence of young compressional features including folds, overthrust and strike-slip faults, have been recognized (Cavallin et al., 1984; Slejko et al., 1986).

We carried out careful kinematic analysis of the Pliocene-Quaternary evolution of the Apennines by integrating surface investigation with subsurface data which mainly derive from oil exploration. Thousand of kilometers of seismic lines and several hundred boreholes permitted the recognition and the tracing, at regional scale, of some well-dated key reflectors. Stratigraphy turned out to be a very useful instrument, giving in this time span a chronological resolution of an average about 400.000 years. Subsurface information concerning the Po Plain mainly derives from Pieri and Groppi (1981).

The results of the kinematic analysis allowed us to divide the Italian Peninsula into two arcs representing two first-order structural elements which are, moreover, underlined by the trend of the Bouguer gravity anomalies. The northern arc, which includes the Northern and the Central Apennines, shows a kinematic evolution dominated, during the whole Pliocene-Quaternary interval, by extension within the Northern Tyrrhenian Sea and adjacent onshore areas and by the compression along the Po-Adriatic front. A counterclockwise rotation of the whole Apenninic chain around a pole located at the western edge of the Po Plain accompanied by dextral strike-slip displacements at the eastern margin of the thrust belt was responsible for the main curvature of the arc. The most prominent surface expression of this dextral strike-slip motion is the so called « Maiella-Roccamonfina line ». The southern arc, which includes the Southern Apennines and the Calabrian Arc, shows in recent times a tectonic evolution quite different from that evidenced in the northern arc. The main compression along the outher margin of the Southern Apennines, in fact, dates back to the middle Pliocene, and more recent compressional features are negligible in substance. During Late Pliocene-Quaternary times, longitudinal faults mostly displaying sinistral strike-slip displacements dissected the mountain chain, with extensional components along the Tyrrhenian margin of the Apennines. In the Calabrian Arc, on the contrary, contemporaneous extension along the inner side and severe compression along the outher side (Rossi and Sartori, 1981; Ghisetti and Vezzani, 1982; Barone et al., 1982) occurred. We would expect dextral lateral motions in Sicily, at the south-western edge of the arc, but we did not sufficiently investigate this area.

The described arcs represent, in our opinion, the response at surface and shallow depths of a differential sinking of the Po-Adriatic-Ionian lithosphere, with maximal retreat at the apex of the two arcs (Fig. 2). We consider this sinking (see Royden and Karner, 1984) a consequence of the passive subduction of a relic and fragmented lithospheric slab inherited from early Miocene times, when the Tyrrhenian basin was not yet open and the western margin of the Adriatic Promontory was still undergoing plate-convergence deformational process (Patacca and Scandone, 1984).

The seismotectonic analysis we carried out followed four principal steps:

– in accordance with the postulate that earthquakes are always and everywhere related to active geological structures, we first examined the major tectonic features of the Italian region, in order to check whether the recoggnized regional structures and the relative kinematics would fit the occurrence of the maximal-magnitude historical earthquakes. It is important to underline that seismogenetic structures are not necessarily expressed at the surface by evident structural or morphological features;

– in the second step we checked whether or not the elongation of the maximal isosimals (filtered from local effects) and the focal mechanisms (when available). of the strongest earthquakes were coherent with the geometry and the kinematics of the recognized active geological structures;

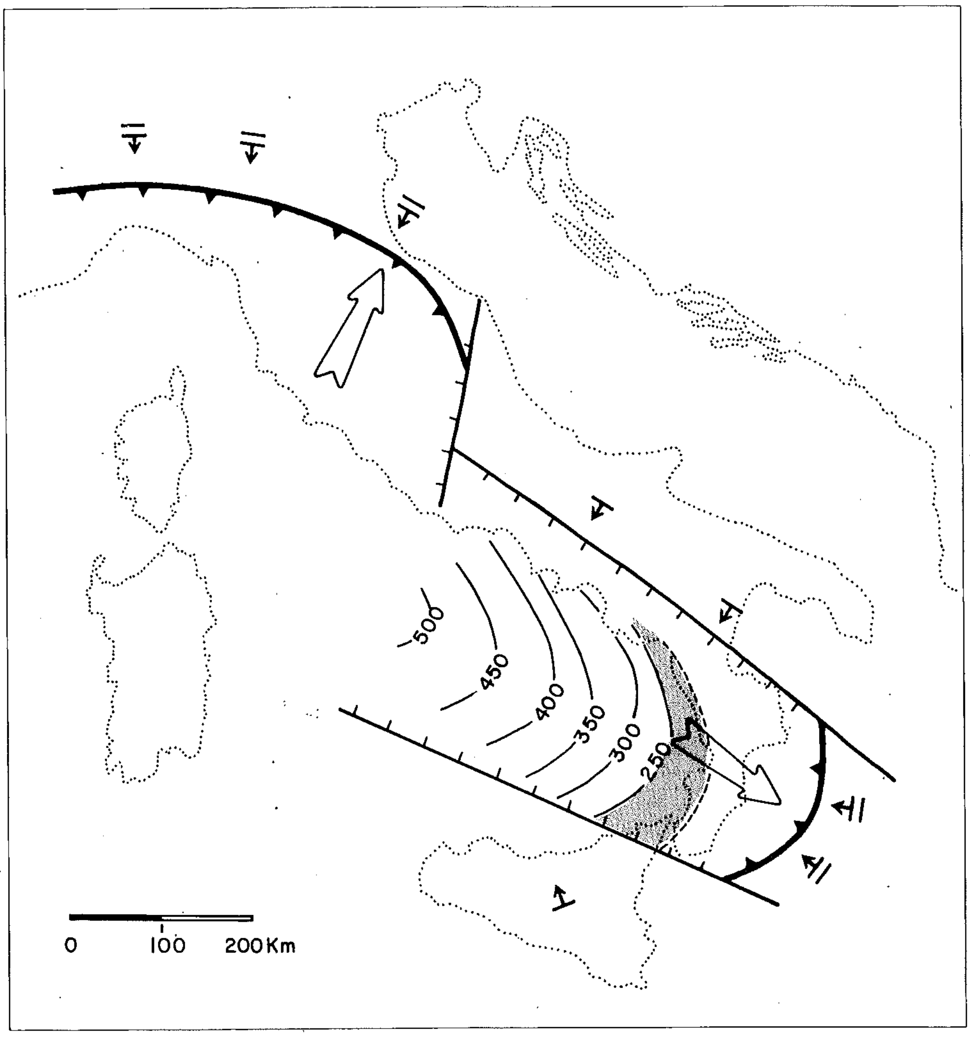

Fig. 2 – Differential sinking of the Po-Adriatic-Ionian lithosphere. White arrows indicate the present-day direction of the orogenic transport at shallow depths. Small arrows describe the sinking of the lithosphere in the northern and southern Apenninic arcs. In the Southern Tyrrhenian Sea, the Ionian lithosphere dips nearly vertical to a depth of about 250 kilometers.

– in the thirth step an interactive re-analysis of all (seismic, structural and stratigraphical) available data allowed ut to include in the kinematic model the minor geological structures which resulted active during Late Pliocene-Pleistocene times. In this way we tried to find correlations even between the kinematic behaviour of the minor active structures and the main characteristics (macroseismic fields, focal parameters) of minor-energy earthquakes;

– the research of the fourth stage, still in progress, is addressed to a better delimitation and definition of the seismogenetic structures in order to obtain (together with the statistical analysis of the historical and present-day seismicity) a better evaluation ot the seismic hazard.

For earthquake analysis we used the recent ENEL-CNR *Geodynamics Project*, revised catalogue (POSTPISCHL Ed., 1985). The macroseismic fields mostly derive from IACCARINO (1968) IACCARINO and MOLIN (1978), BARBANO et al. (1980), POSTPISCHL Ed. (1985), BRANNO et al., (1986). Most of the data concerning focal mechanisms is reported from GASPARINI et al. (1980), GASPARINI et al. (1982), CELLO et al. (1982), CAVALLIN et al. (1984), CAPPONI et al. (1980).

Plate 1 shows the main structural features of the Italian region, the reconstructed main-damage areas of destructive earthquakes occurred after 1000 A.D., and the local stress-fields deduced by focal-mechanism solutions.

The principal results of our research, at the present stage, are the following:

– different stress-fields, related to different sources, coexist in the Italian Peninsula and surrounding areas;

– the NW-SE strikes of the nearly-horizontal P axes of some crustal and deep-focus earthquakes perfectly fit the regional stress-field of the central Mediterranean region (MUELLER, 1984). This long-period stress-field is induced by the present day interaction between the African and the European plates. The stress accumulation releases at the boundaries of the Adriatic Promontory (e.g. Friuli 1976 earthquake), as well as inside the rigid block, along the major faults (e.g. Gargano 1975 and, probably, 1927 earthquakes). The indipendent countercloclakwise rotation of the Adriatic Promontory, if still active today, should induce an additional stress field which might be responsible for a part of the Eastern-Alps seismicity; it is very difficult, in any case, to discriminate this stress field from the regional one;

– the seismicity of the Central and Western Alps is very low in comparison with the seismicity of the Eastern Alps and the Apennines, demonstrating that some parameters often assumed to be prognostic for seismogenetic active structures (e.g. sharp gradient of the Bouguer gravity anomalies, high rates of uplift, occurrence of very long morphological-structural lineaments) must be considered with caution in seismotectonic analysis;

– in the Apennines, the kinematically-distinguished northern and southern arcs display different patterns of seismicity distribution, as well as different seismotectonic potentials, with the occurrence of higher-magnitude events in the southern arc (PANZA et al., 1981). The kinematic evolution of the two arcs has been strictly controlled by the Po-Adriatic-Ionian sinking lithosphere and by the contemporaneous extensional processes in the Tyrrhenian

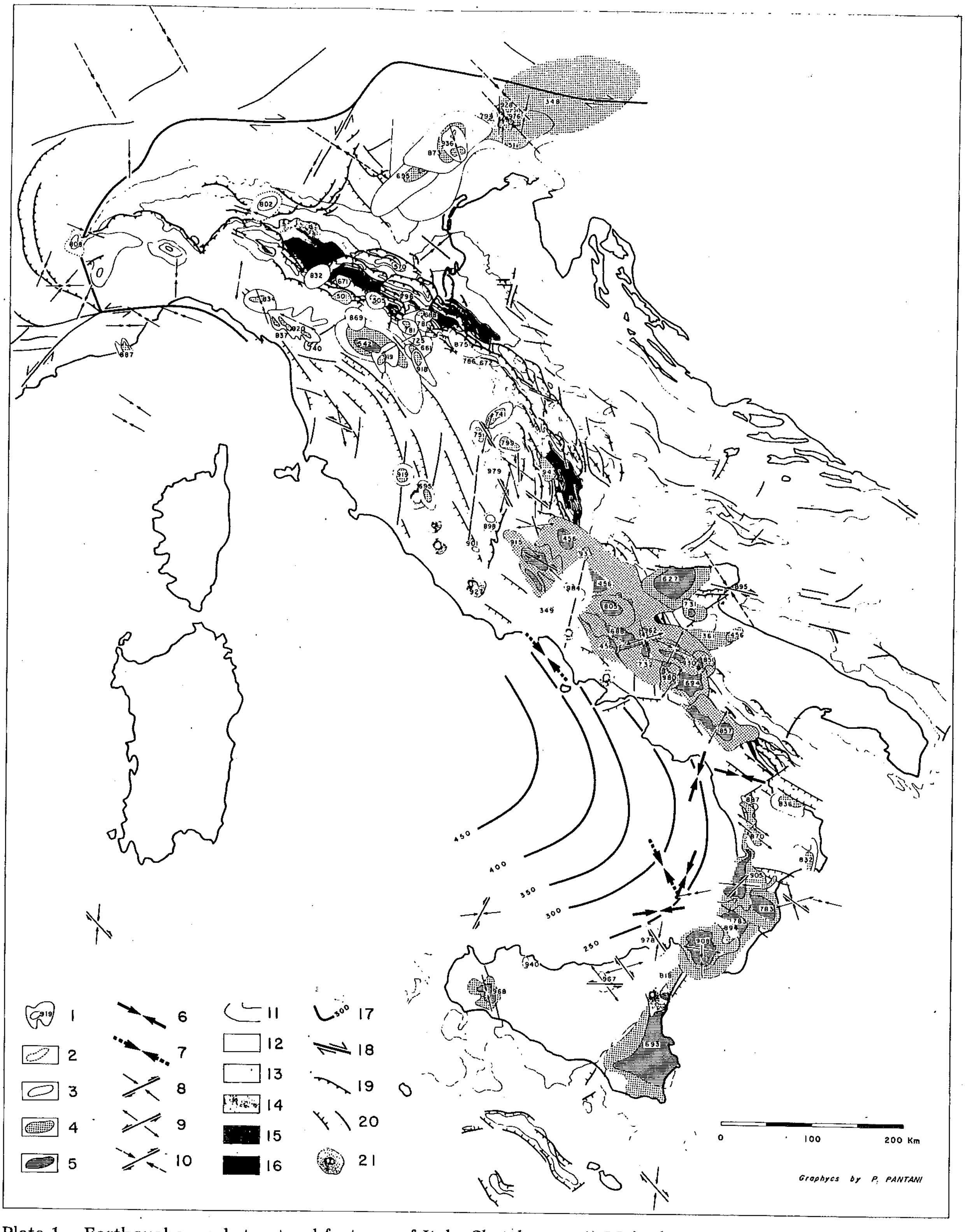

Plate 1 – Earthquakes and structural features of Italy. Sketch map: 1) Main-damage areas of destructive earthquakes after 1000 A.D.: VII MCS (2); VIII MCS (3); IX MCS (4); X and XI MCS (5); 6) Strikes of nearly-horizontal P-axes of deep-focus and intermediate earthquakes; 7) id. id., coinciding with the direction of the regional stress in the Central Mediterranean region; 8) Strikes of nearly-horizontal P-axes of shallow earthquakes. In some cases, the presumed fault-planes and the direction of the first motion have been reported; 9) id. id., coinciding with the direction of the regional stress in the Central Mediterranean region; 10) Strikes of nearly-horizontal T-axes of shallow earthquakes. In some cases, the presumed fault-planes and the direction of the first motion have been reported; 11) Isobaths of the base of the Pliocene-Quaternary deposits overlying the Po-Adriatic-Ionian foreland: 0-0.5 km. (12); 0.5-2.0 Km. (13); 2.0-3.5 Km. (14); 3.5-5.0 (15); > 5.0 Km. (16); 17) Isobaths (in kilometers) of the subducted lithosphere (Southern Tyrrhenian Sea); 18) Lithospheric faults; 19) Overthrusts; 20) faults. Where possible, the downthrow side and the direction of the lateral motion (arrows) have been indicated; 21) Quaternary subaerial volcanoes.

area. Following such a model, we should distinguish between seismic sources located in the flexure zone of the Po-Adriatric-Ionian lithosphere, where the latter is sinking beneath the Apennines, and seismic sources located within the more ductile Apenninic crust;

– deep-focus earthquakes occur in the southern arc and not in the northern one, in spite of the comparable geodynamic processes acting on the two regions. We have no reasonable explanation of this fact which would require anelastic deformations in the Po-Adriatic lithospheric fragment underlying the Northern Apennines and an elastic-energy release in the fragment underlying the Calabrian Arc;

– in the northern arc, two principal seismogenetic areas have been recognized in the crust (Eva et al., 1978) which are located along the outer margin of the Apenninic chain and along the inner one. The outer margin is characterized by a compressional stress field with nearly-horizontal P axes oriented normal to the strike of the main geological structures. Earthquakes are usually generated at shallow depths, although a deepening of the focuses is recognizable (Console and Favali, 1981) moving from the most external compressional fronts towards the foot of the mountain range. The deepening of the focuses follows the deepening of the Po-Adriatic crust beneath the Apennines (see Plate 1). Ferrara 1570, Argenta 1624, Cotignola-Bagnacavallo 1988 and Modena 1901 can be considered representative examples of destructive events related to the described compressional stress-field. The second seismogenetic area in the Norther Apennines (Lunigiana-Garfagnana, Mugello, Upper Tiber Valley) follows the present-day front of the Tyrrhenian extension which runs close to the orographic divide of the mountain chain (Mazzanti and Trevisan, 1978). Transverse active structures (see, e.g. earthquakes of the Forlivese area) connect the compressional and the extensional margins of the Northern Apennines Most of these structures play the kinematic role of source-sink strike-slip faults;

– in the southern arc two segments may be distinguished. The northern segment, which extend from Abruzzi to the Taranto Gulf, has been shocked in historical times by several destructive events originating within a narrow seismogenetic area (see Table 1), which roughly following the orgenic divide of the mountain range. The southern segment, corresponding to the Calabrian Arc *sensu stricto*, is characterized by deep earthquakes related to the passive sinking of the Ionian lithosphere and by a complex pattern of shallow seismicity resulting from compressional processes along the outher margin of the arc and coeval extensional processes along the inner one (Gasparini et al., 1982; Ghisetti et al., 1982). Furthermore, an additional stress-field is induced by the increasing curvature of the arc, with consequent compression in the concave part and stretching in the convex one; the curvature increase has been accompanied by strike-slip displacement along vertical surfaces transversal to the regional trend of the thrust belt;

– subsurface exploration in the Southern Apennines clearly shows that the epicentral areas of some destructive earthquakes (e.g. Irpinia 1930) lie above the sinking margin of the Apulia foreland, demonstrating that the corresponding seismogenetic structures are not located within the Apenninic crust. We do not exclude the possibility that all the high-magnitude earthquakes of the Southern Apennines, as well as the major-energy earthquakes of the internal seismogenetic zone of the Northern Apennines, originate from fracture zones in the Po-Adriatic crust which follows the maximal gradient of the foreland lithosphere flexure.

We are perfectly conscious of our inadequate knowledge of seismogenetic processes, and we consider the above considerations as preliminary results which need to be carefully checked and markedly improved. Nevertheless, we believe that some conclusions concerning the identification of the seismic sources, the seismic regionalization, and the expected focal mechanisms in the major seismogenetic structures are already utilizable to integrate the historical seismic data in order to obtain a more realistic evaluation of the seismic hazard of the Italian region. Obviously, our approach does not permit the selection of parameters which are significant in every geological condition, so that it can not lead – in the present stage of research – to a model which might apply outside of the investigated area. In our opinion, extensive seismotectonic analysis of disparate geological regions carried out following a kinematic approach could provide, in the future, a wider data sample which might be suitable for generalization and modelling. This process is long and difficult, and success is not assured. On the other hand, we are deeply convinced that no short cuts exist in the seismotectonic analysis and that definite models which can appear brilliant and logical may include, in reality, so much oversimplification that they may, in the long term, turn out to be dangerous boomerangs to a serious safety policy.

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