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Seismic Hazard of the Circum-Pannonian Region

Edited by
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Pure and Applied Geophysics

Preface

The Circum-Pannonian Region extends over a relatively large territory from Central to Eastern Europe including densely populated and industrialized areas in several countries. While the highest seismic hazard is controlled at a regional scale by the large Vrancea intermediate-depth earthquakes, several shallow earthquake-prone areas are very important at a local scale. In the present geopolitical context of Europe, the harmonization of Western and Eastern Europe in terms of seismic safety compliance appears crucial for the future development and prosperity of the whole continent. This special volume summarizes the outcome of several international projects conducted over recent years, such as *Quantitative seismic zoning of the Circum-Pannonian Region* (EC-Copernicus), *Earthquake hazard associated with the Vrancea region seismicity* (NATO), and *Microzonation of Bucharest, Russe and Varna cities in connection with Vrancea Earthquakes* (NATO).

The above projects have resulted in a high degree of innovation. Effective state-of-the-art techniques have been developed for the assessment of seismic hazard, and reliable ground motion estimates were obtained. This collection gathers fourteen original studies which offer quantitative information required for the design, construction and retrofitting of the built environment that will greatly reduce the number of human casualties and the amount of property loss due to a large earthquake that may occur in this region or its vicinity. In particular, it is important to outline the impact of these studies on the reduction of the environmental hazard associated with the existing four nuclear power plants in the region. As such, the results obtained should be considered a starting point for subsequent and more detailed investigations into the retrofitting of the nuclear plants in Bulgaria, Hungary, Romania and Slovenia. Additionally, these studies have significantly contributed to the establishment of the source and response spectra to be used in connection with the large intermediate-depth earthquakes generated by the Vrancea region of Romania. The results also suggest the working hypotheses that could be further employed for an integration and revision of the European Building Code EC8.

An initial group of papers employs the analysis of the seismicity pattern, main geologic structures and geodynamic models, in their attempt to characterize the seismogenically active areas and define the provinces of seismogenic homogeneity. As such, the introductory study by *Meletti et al.* outlines a working methodology that has been employed in the seismotectonic zonation of Italy for hazard assessment purposes. The paper by *Poljak et al*. integrates information on seismicity, earthquake mechanisms, displacement rates and stress estimates to delineate and characterize the seismogenic areas of the territory of Slovenia. Similarly, *Radulian et al*. review and update the available information in their effort to identify the principal features of the seismogenic areas active on the territory of Romania, with a special reference to the Vrancea zone.

The next group of papers includes a few theoretical observational studies aimed to providing additional support for the delineation of earthquake-prone areas, source parameters, and structural models that may be further used in seismic hazard assessment. The work by *Gorshkov et al*. represents an application of the morphostructural analysis to the block-structure of the regional crust. Their results appear to correlate well with the recorded seismicity, except for the northeastern zone of the Vrancea region, where significantly lower seismic intensities have been recorded to date. The dynamics of the Vrancea region is the subject of a study by *Soloviev et al*. Using a block model, they concluded that a variation in model parameters has little effect on the orientation of the fracture slip for the intermediate-depth events. Based on a 2-D finite-element model of a sinking slab, *Ismail-Zadeh et al*. find a good correlation between the depth distribution of stress in Vrancea and the recorded seismicity and energy release. However, since the annual cumulative seismic moment estimate far exceeds that expected for a pure phase-transition, they consequently suggest dehydration of rocks as the triggering mechanism of these events. On a different topic, *Živčić et al*. use surface-wave dispersion analysis to derive the velocity distribution beneath the territory of Slovenia.

The main focus of this volume is the quantitative seismic zoning. Traditional methods use either a deterministic or probabilistic approach, based on empirically derived laws for ground motion attenuation. The work by *Musson* is a good exemplification of the probabilistic approach, the results of which are subsequently compared and found in good agreement, except for the Vrancea zone, with the results of a deterministic approach. In the case of Vrancea, the attenuation relations used in the probabilistic approach seem to underestimate, mainly at large distances, the seismic hazard due to the intermediate-depth earthquakes, whereas the deterministic results seem representative of the most conservative scenario. Recent advances in computer technology, however, now make possible the use of the deterministic numerical synthesis of ground motion for seismic hazard calculations. The deterministic approach capably addresses aspects largely overlooked in the probabilistic approach, such as: (a) the effect of crustal properties on attenuation: (b) the derivation of ground motion parameters from synthetic time histories, instead of using highly simplified attenuation functions; (c) the direct evaluation of resulting maps in terms of design parameters, without requiring the adaptation of probabilistic maps to design ground motions; and (d) the generalization of design parameters to locations where there is little seismic history. Maximum displacements, velocities, and, based on the European Building Code EC8, design ground acceleration maps have thus been produced by *Živčić et al.* for Slovenia, *Markušić et al.* for Croatia, *Bus et al.* for Hungary, and *Radulian et al.* for Romania.

The last two contributions in the volume are dedicated to studies of local site effects that could affect the microzonation of large urban areas. *Moldoveanu et al.* employed a technique based on the modal summation and finite differences to calculate the expected ground motion in the capital city of Bucharest due to large intermediate-depth Vrancea earthquakes. Their results outline that the presence of alluvial sediments and the possible variation of event scenario require the use of all three components of motion for a reliable determination of the seismic input. The study of *Marmureanu et al.*, more limited in scope, offers a laboratory analysis of the attenuation effects for surface layers. The authors confirm that seismic attenuation in sedimentary layers is a function of the strain levels induced by large earthquakes, and find that the quality factor is nearly constant over a relatively wide frequency range, between 7 and 100 Hz.

Acknowledgements

This collection of papers gathers contributions from numerous authors, who are acknowledged both for the quality of their work and the interest in contributing to a special volume. Additionally, this volume was made possible due to the dedicated work of numerous reviewers whose time, conscientious efforts and scientific judgement have been oriented to ensuring that the scientific community will circulate a sound and efficient message. As such, *Karim Aoudia*, *Kuvvet Atakan*, *Gail Atkinson*, *Igor Beresnev*, *Guenter Bock*, *Jean Bonnin*, *David Boore*, *Hilmar Bungum*, *Peter Byrne*, *Armando Cisternas*, *Rodolfo Console*, *Torsten Dahm*, *Catherine Dorbath*, *John Ebel*, *Mariana Eneva*, *Bob Engdhal*, *Mustafa Erdik*, *Andrew Feustel*, *Liam Finn*, *Clifford Frohlich*, *Gotfried Grunthal*, *Susan Hough*, *Steven Jaume*, *Andrzej Kijko*, *Raul Madariaga*, *Tina Nunziata*, *David Oppenheimer*, *Robert Pearce*, *David Perkins*, *Avi Shapira*, *Hong Kie Thio*, *Colin Thomson*, *Augustin Udias*, *Jean Virieux*, *Friedemann Wenzel*, *Jiri Zahradnick* are warmly thanked for willingly accepting the above responsibility and providing competent reviews. Finally, we would like to express our gratitude to *Miguel Angel Virasoro*, Director of the Abdus Salam International Center for Theoretical Physics (ICTP), to *Giuseppe Furlan*, Head of the ICTP program for Training and Research in Italian Laboratories, and to *Lucio Delcaro*, Rector of the University of Trieste, for their encouragement and support.

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Pure and Applied Geophysics

Introduction

The complex logistic problem connected with transnational seismic zoning and microzoning following standardized criteria has greatly benefited from the existing organizational network established in the framework of the Earth Sciences Committee of the Central European Initiative.

The results contained in this special issue offer information necessary to greatly reduce the number of human casualties and the amount of property loss upon the occurrence of a big earthquake in a large part of Southeast Europe and North-Africa.

Given the number of nuclear power plants located in the studied region, the results of the present study *should* be used as a starting point for successive more detailed investigations aimed at the retrofitting of the existing plants. This may be a necessary action in order to reduce the environmental hazard associated with such plants.

Maps of various seismic hazard parameters numerically modelled, and whenever possible tested against observations, such as peak ground displacement, velocity and acceleration, of practical use for the design of earthquake-safe structures, have been produced, in combination with the first microzoning actions in large cities, such as Bucharest, Ljubljana and Sofia. The *Realistic Modelling of Seismic Input for Megacities and Large Urban Areas is presently a major commitment of UNESCO-IGCP, under its project 414.*

The synoptic analysis of the seismicity pattern, of the main geologic structures and of the geodynamic models, provided the starting point for the characterization of the seismogenically active areas and the means to define the provinces of seismogenic homogeneity. A regional seismic catalogue has been compiled with national catalogues, and earthquake mechanism and size have been determined for each seismogenic area, with the key contribution of local experts. The simultaneous involvement of scientists from the different countries has allowed a minimization of the effects of political boundaries, quite often hampering such studies.

In Figures 1–3 we show maps of the peak values of horizontal motion (displacement, D, velocity V, and design ground acceleration, DGA) for the European/Mediterranean countries that have contributed to this major effort for the mitigation of seismic hazard. For more details, see the national studies.

The peak values of D, V and DGA, and pertinent periods T(D) and T(V), at the sites where nuclear power plants are located are summarized in Figure 4. The values obtained at Cernavoda, Kozloduy and Paks are controlled by the intermediate-depth Vrancea events ($M = 7.7$)

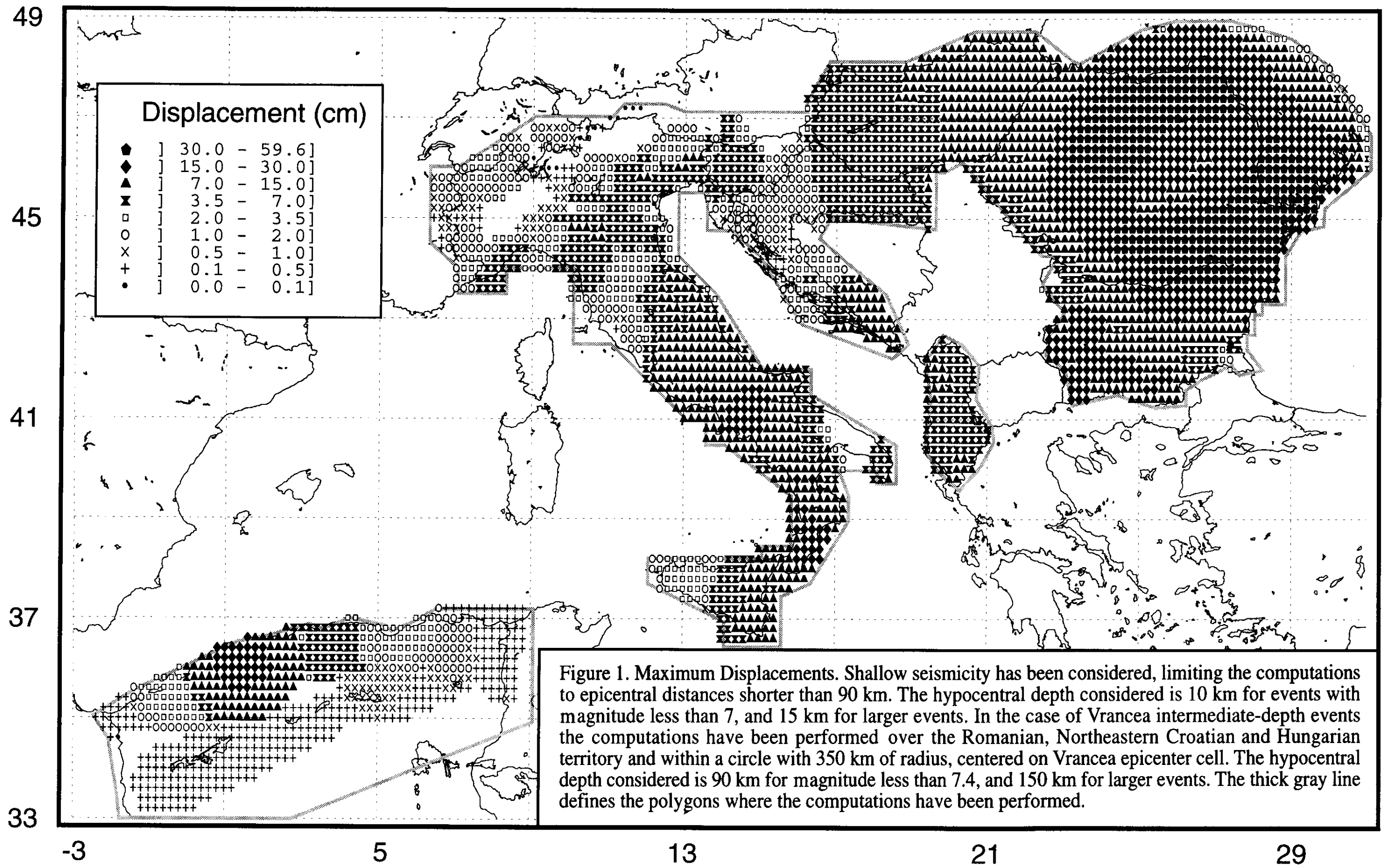

Figure 1. Maximum Displacements. Shallow seismicity has been considered, limiting the computations to epicentral distances shorter than 90 km. The hypocentral depth considered is 10 km for events with magnitude less than 7, and 15 km for larger events. In the case of Vrancea intermediate-depth events the computations have been performed over the Romanian, Northeastern Croatian and Hungarian territory and within a circle with 350 km of radius, centered on Vrancea epicenter cell. The hypocentral depth considered is 90 km for magnitude less than 7.4, and 150 km for larger events. The thick gray line defines the polygons where the computations have been performed.

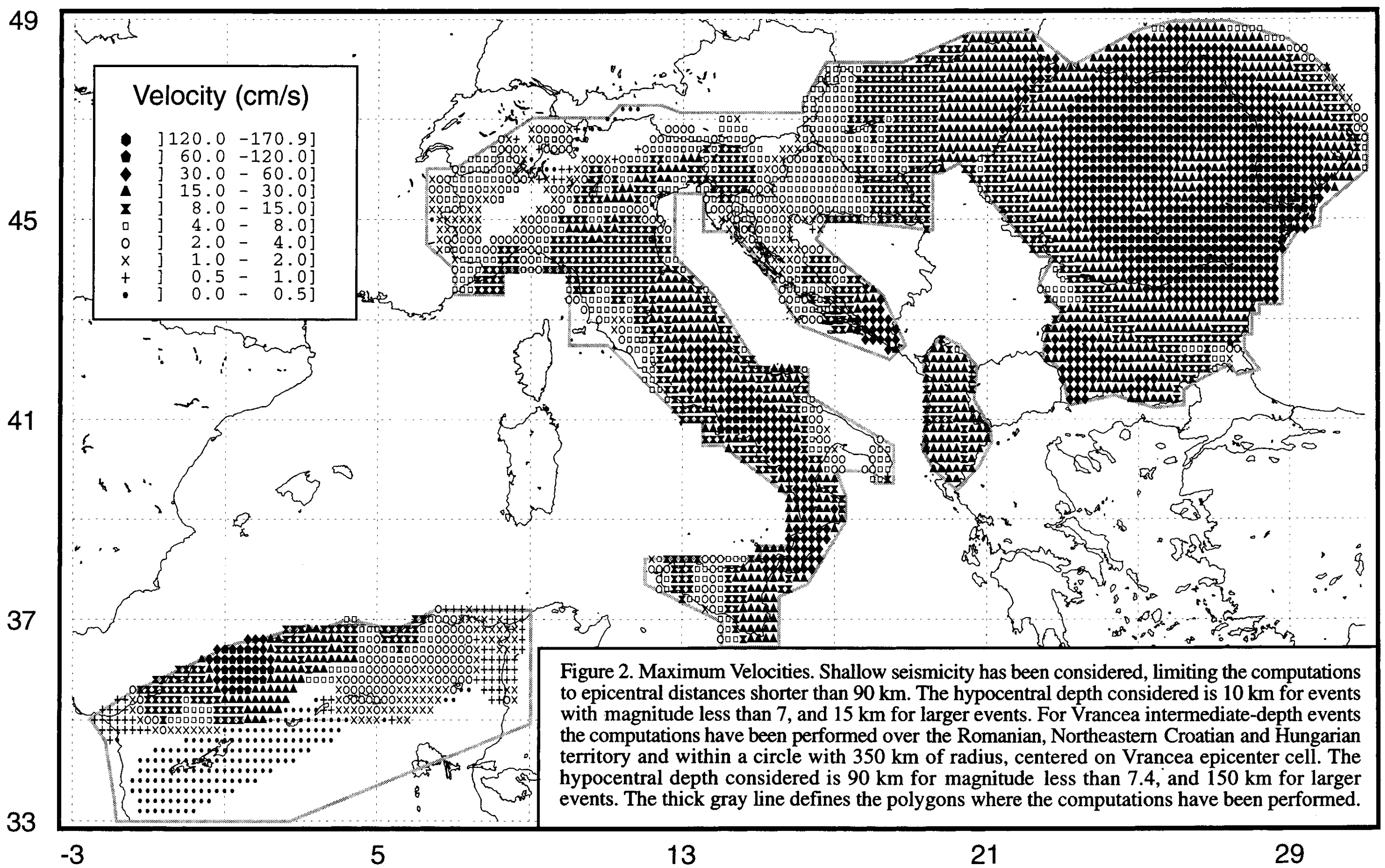

Figure 2. Maximum Velocities. Shallow seismicity has been considered, limiting the computations to epicentral distances shorter than 90 km. The hypocentral depth considered is 10 km for events with magnitude less than 7, and 15 km for larger events. For Vrancea intermediate-depth events the computations have been performed over the Romanian, Northeastern Croatian and Hungarian territory and within a circle with 350 km of radius, centered on Vrancea epicenter cell. The hypocentral depth considered is 90 km for magnitude less than 7.4, and 150 km for larger events. The thick gray line defines the polygons where the computations have been performed.

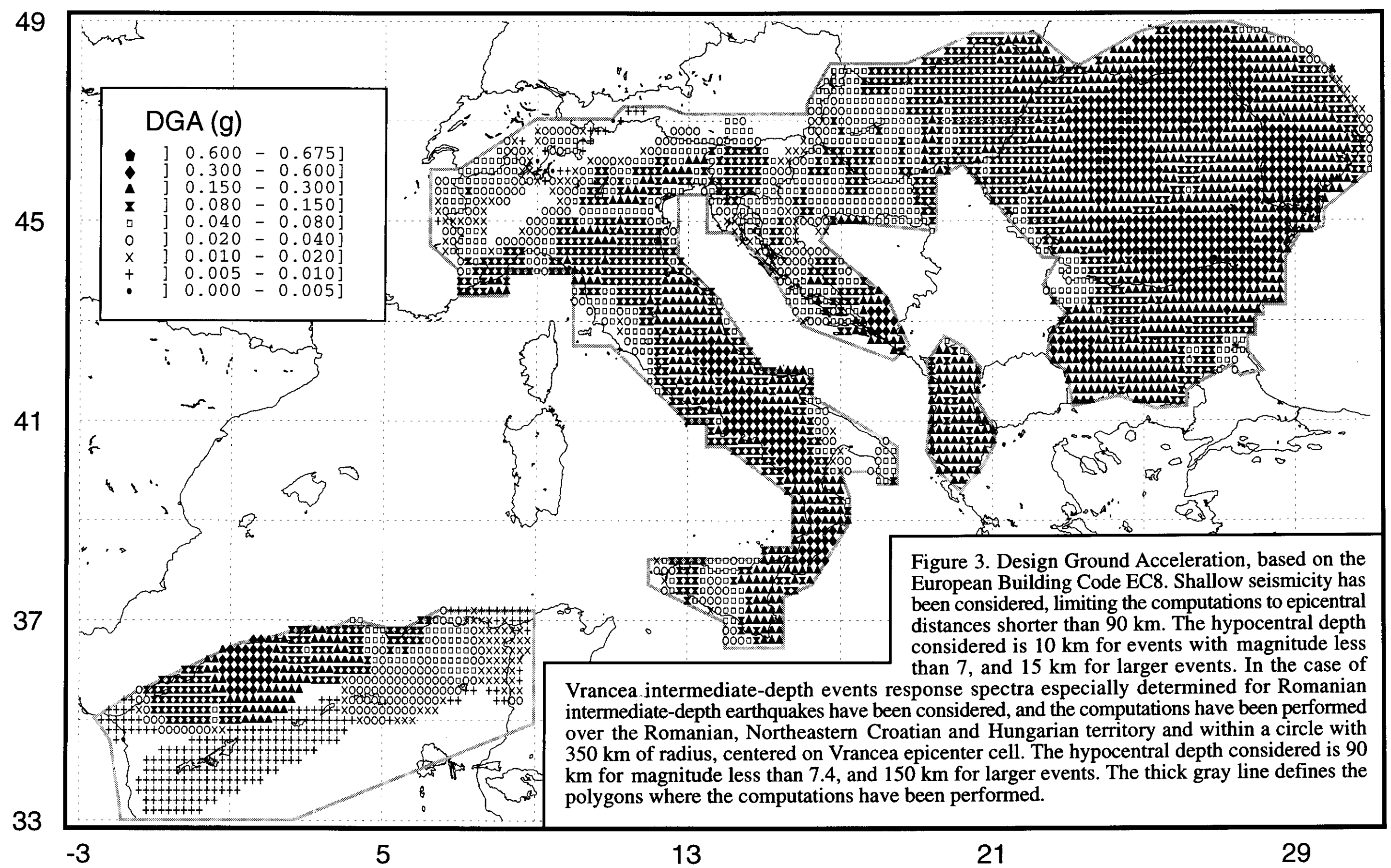

Figure 3. Design Ground Acceleration, based on the European Building Code EC8. Shallow seismicity has been considered, limiting the computations to epicentral distances shorter than 90 km. The hypocentral depth considered is 10 km for events with magnitude less than 7, and 15 km for larger events. In the case of Vrancea intermediate-depth events response spectra especially determined for Romanian intermediate-depth earthquakes have been considered, and the computations have been performed over the Romanian, Northeastern Croatian and Hungarian territory and within a circle with 350 km of radius, centered on Vrancea epicenter cell. The hypocentral depth considered is 90 km for magnitude less than 7.4, and 150 km for larger events. The thick gray line defines the polygons where the computations have been performed.

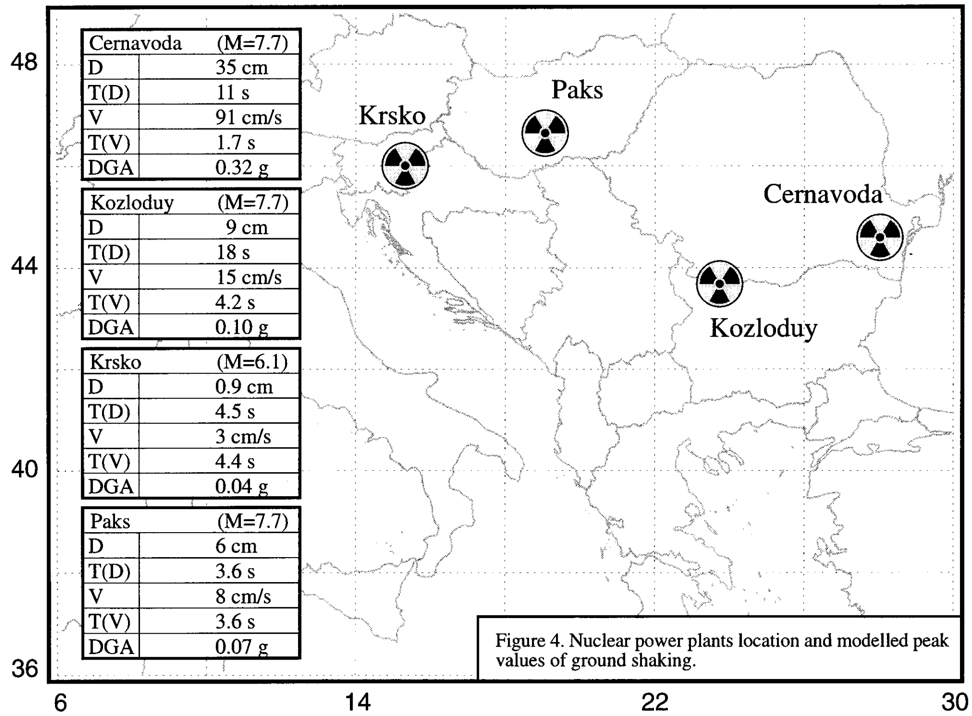

Figure 4. Nuclear power plants location and modelled peak values of ground shaking.

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The comprehensive maps defining the deterministic seismic hazard have been also made possible by the contribution of Prof. B. Muço (for Albania, unpublished). Special thanks are extended to Acad. Prof. V. I. Keilis-Borok who attracted our attention to the problem of the seismic hazard connected with the Vrancea earthquakes.

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Realistic Modelling of Seismic Input for Megacities and Large Urban Areas (project 414)

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Pure and Applied Geophysics

Construction of a Seismotectonic Model: The Case of Italy

Carlo Meletti,[1] Etta Patacca[2] and Paolo Scandone[2]

Abstract—Procedures for constructing a seismotectonic model of Italy, designed to be used as a basis for hazard assessment, are described. The seismotectonic analysis has essentially been based on a GIS-aided cross-correlation of three data sets concerning:

– the 3-D structural model of Italy and surrounding areas;
– the space distribution of historical and present seismicity;
– the kinematic model of the Central Mediterranean region, referred to the last 6 Ma and including the available information on the present-day plate motion and stress field.

The seismicity pattern in the study area is controlled by a quite complex geodynamic framework which includes:

– continent–continent convergence (Alps and Dinarides) with development of a neutral arc bordering the plate margins;
– plate divergence across margins characterized by passive slab sinking (Northern Apennines and Calabrian Arc), with development of backarc basins (Northern Tyrrhenian Sea and Southern Tyrrhenian Sea) flanked by forelandward migrating thrust belt-foredeep systems;
– plate divergence across a margin previously characterized by lithosphere sinking and afterwards discharged from the subducted slab (Southern Apennines), with development of quite peculiar rift processes within the inactive thrust belt;
– transpression (Northern Sicily) due to the combined effect of plate convergence (Africa-Europe) and high-rate flexure-hinge retreat of an intervening plate (Adria microplate) with high angles between the respective slip vectors;
– intraplate strain partition and fault activity (mainly combined strike-slip and thrust motions), possibly in correspondence of inverted structures.

The results of the seismotectonic analysis are synthesized in a zonation of Italy in which every delimited zone corresponds to the surface projection of a kinematically-homogeneous segment of a seismogenic fault system. In Cornell-type hazard evaluations every polygon should be considered as a homogeneous source-zone, seat of randomly-distributed earthquakes. A homogeneous mechanical behaviour of an entire zone and a random earthquake-distribution within a single source zone obviously represent oversimplified assumptions since every zone includes one or more master-fault segments responsible for the greatest events in the area and several second-order associated faults responsible for the background minor seismicity. Therefore, major faults and background seismicity should be treated separately. Nevertheless, the oversimplified assumption of homogeneous seismic zones was the price the authors consciously paid to produce, in a reasonably short time, a homogeneous product relative to the entire national territory, suitable for earthquake hazard evaluation and for decisions regarding risk mitigatiton.

Key words: Seismotectonics, Italy, kinematic model, seismic zonation, seismic hazard.

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1. Foreword

The seismotectonic zonation of an earthquake-prone region, that is the identification, delimitation and characterization of seismogenic geological structures, is a preliminary basic operation for achieving realistic assessments of the seismic hazard. Obviously, the adopted seismic zonation influences, and in some cases (see CORNELL, 1968; BENDER and PERKINS, 1987) closely controls, the distribution pattern of the hazard results. Unfortunately, neither a univocal approach nor standard procedure has been established to date by the scientific community (BASHAM and GIARDINI, 1993; GIARDINI and BASHAM, 1993) in order to produce in different countries seismotectonic zonations based on homogeneous or at least comparable criteria (see, e.g., GRELLET *et al.*, 1993; GRÜNTHAL *et al.*, 1995; LENHARDT, 1995; PAPAZACHOS, 1988, 1996; SCANDONE *et al.*, 1992; VOGT and GODEFROY, 1981). Consequently, different parameters have been preferred by different researchers in order to perform seismotectonic investigations. In some cases this is due to the wide variety of geological scenarios (geodynamic regime, tectonic style, kinematic evolution, etc.), but more often it is because of dissimilar basic assumptions and philosophical approaches (see, among many others, ALLEN, 1976; BORISOV *et al.*, 1976; BUNE *et al.*, 1974; CISTERNAS *et al.*, 1985; D'OFFIZI, 1994; GELFAND *et al.*, 1972; HAYS, 1980; IAEA SAFETY GUIDE, 1991; LAVECCHIA *et al.*, 1994; MUIR-WOOD, 1993; MULARGIA *et al.*, 1987; PANTOSTI and YEATS, 1993; PATACCA and SCANDONE, 1986; SCHICK, 1978; SCHWARTZ and COPPERSMITH, 1986; SLEMMONS and DEPOLO, 1986; TRIFONOV and MACHETTE, 1993; WALSH and WATTERSON, 1988; WELLS and COPPERSMITH, 1994; WORKING GROUP ON CALIFORNIA EARTHQUAKE PROBABILITIES, 1995; ZOBACK, 1993).

In this paper we shall briefly describe procedures and results of seismotectonic analysis of Italy carried out within the framework of the scientific activities of the CNR-Gruppo Nazionale per la Difesa dai Terremoti (National Group for the Defense against Earthquakes, National Council of Research). The results of this analysis are synthesized in a zonation of Italy (Figs. 8, 9) in which every delimited zone corresponds to the surface projection of a kinematically-homogeneous segment of a seismogenic fault system (see SCANDONE *et al.*, 1992). In Cornell-type hazard evaluations every polygon should be considered as a homogeneous source-zone, seat of randomly-distributed earthquakes. A homogeneous mechanical behaviour of an entire zone and a random earthquake-distribution within a single source zone obviously represent oversimplified assumptions since every zone includes one or more master-fault segments responsible for the greatest events in the area, and several second-order associated faults responsible for the background minor seismicity. Therefore, major faults and background seismicity should be treated separately. Actually, current research has been addressed to discriminate between capable fault segments and associated minor faults, as well as to investigate the kinematic and mechanical behaviour of the active master faults responsible for the major ($M \geq 5.5$) crustal earthquakes. Nevertheless, the available paleoseismological information (see among others BRUNAMONTE *et al.*, 1991; CELLO *et al.*, 1997; CINTI *et al.*, 1997; FERRELI *et al.*, 1996; GALADINI *et al.*, 1996; GHISETTI, 1992; MICHETTI *et al.*, 1996; PANTOSTI *et al.*, 1993, 1996; SERVA *et al.*, 1986; VALENSISE and PANTOSTI, 1992; WARD and VALENSISE, 1989) is still too patchy for the application of hybrid methods of hazard evaluation (e.g., PERUZZA *et al.*, 1997) over the entire Italian territory. Therefore, the oversimplified assumption of homogeneous seismic zones was the price we consciously paid to produce, in a reasonable short time, a homogeneous product relative to the entire national territory. In the present state of the art, the zonation of Figures 8 and 9 has been adopted as an input framework for earthquake hazard evaluations (COSTA *et al.*, 1993; PANZA *et al.*, 1998; ROMEO and PUGLIESE, 1997; SLEJKO, 1996; SLEJKO *et al.*, 1998) used by political authorities for decisions regarding risk mitigation in Italy. In addition, seismotectonic regionalization combined with earthquake epicentres and focal mechanisms has been used for intermediate-term earthquake forecasting (BOSCHI *et al.*, 1995b; COSTA *et al.*, 1995, 1996).

The aim of this paper is to discuss the methodology we followed for the seismotectonic analysis and to describe the general results in terms of source geometry and kinematics. Special emphasis will be placed on the contribution given to the seismotectonic analysis by a kinematic approach (PATACCA and SCANDONE, 1986) in order to fix reliable constraints to the possible correlation between seismicity and active geological structures in complex thrust-and-fold belts like the Alps and the Apennines.

2. Geological Framework

The Neogene-Quaternary kinematic evolution and the present-day stress field of the Central Mediterranean area, together with the tectonic structure of Italy (Fig. 1), have often been described as a direct result of the Africa-Europe convergence (e.g., BEN AVRAHAM *et al.*, 1990; BOCCALETTI and DAINELLI, 1982; DEWEY *et al.*, 1973, 1989; MAZZOLI and HELMAN, 1994). Nevertheless, the available geological and geophysical information suggests a more complex plate interaction, with an important role played by the intervening Adria microplate (see ANDERSON and JACKSON, 1987a). In addition, other geodynamic processes, mostly related to a passive sinking of the subducting Adria lithosphere, must be taken into account. In the Apennines these processes are responsible for the migration of the thrust belt/foredeep system towards the Padan-Adriatic-Ionian foreland, and for the synchronous opening of the Tyrrhenian backarc basin according to slip vectors largely exceeding the values of the Africa-Europe convergence (see, among many others, MALINVERNO and RYAN, 1986; MANTOVANI *et al.*, 1996; PATACCA and SCANDONE, 1986, 1989; PATACCA *et al.*, 1990, 1993). The present-day seismicity in the Central Mediterranean region (AMATO *et al.*, 1997; ING, 1995) mostly follows the principal mountain chains, that is the Alps, the Apennines and the Dinarides, though clusters of epicentres indicate a certain fragmentation of the foreland areas, notably in Southern Sicily and in the Sicily Channel, in the Gargano-Tremiti region and in the Central Adriatic Sea (Fig. 2).

The Alps are a well-known thrust-and-fold belt comprising a huge pile of basement and cover nappes transported towards the European foreland, detached from the lower (Europe) and the upper (Adria) plates, as well as from the Jurassic-Cretaceous Tethys Ocean (see CNR, P.F. GEODINAMICA, 1990). Recent

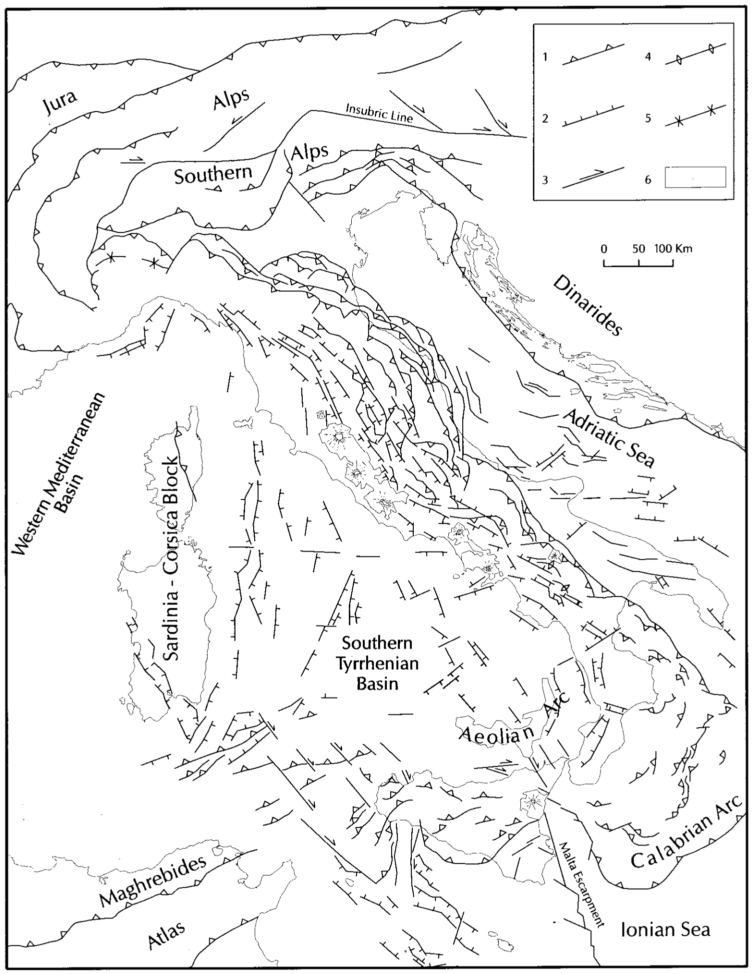

Figure 1
Structural sketch of Italy and surrounding regions. 1 thrusts; 2 normal faults; 3 strike-slip faults; 4 Pliocene-Quaternary anticlines; 5 Pliocene-Quaternary synclines; 6 backarc basins floored by oceanic crust.

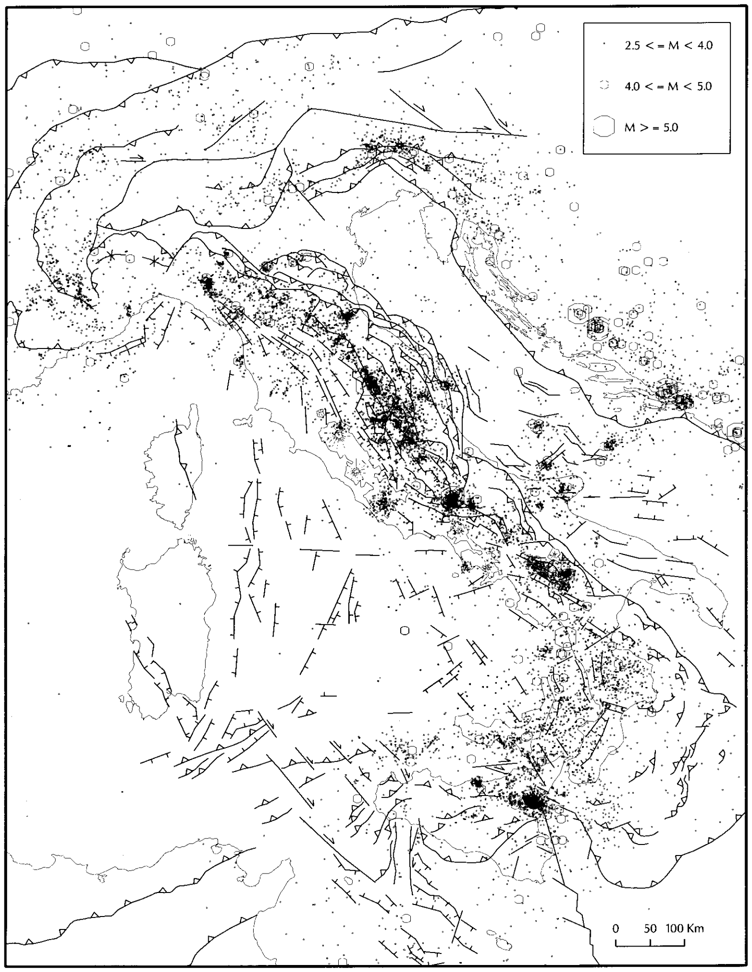

Figure 2
Present-day seismicity in Italy and surrounding areas plotted on the structural sketch of Figure 1. Seismicity from ING (1995).

reflection seismic profiles across the Western and Central Alps (ROURE *et al.*, 1990; SCHMID *et al.*, 1996) display a clear image of the plate boundary in this sector, with a deep-seated triangle zone responsible for the back-thrusting of the Adria lower crust in the Ivrea zone and for the piling up of south-verging imbricate fans in the Southern Alps originated by detachment processes in the upper plate. As regards the Southern Alps, the maximum shortening has been calculated in the eastern part of the system (CASTELLARIN, 1978) where the Alpine structures join those of the Dinarides, and where the strongest historical earthquakes of the Alps have been recorded (e.g., 1976 Friuli earthquake, $M = 6.5$).

The boundary between the Alps and the Apennines corresponds to a transform fault zone which linked through Tertiary and Quaternary times two orogenic systems generated by opposite lithosphere subductions: Europe beneath Adria in the Alps; Adria beneath Europe in the Apennines. The Apennines (including the Calabrian Arc and the Sicilian Maghrebides) form the backbone of the Italian Peninsula and Sicily. This mountain chain constitutes a pile of Adria/Africa verging nappes, mostly cover nappes, detached from the Adria and Africa continental margins, overlain by Tethyan ophiolitic units and (Calabrian Arc) by continental-basement nappes whose original paleogeographic domains are still controversial (CNR, P.F. GEODINAMICA, 1990).

Subduction of Adria beneath Europe started because of active convergence processes in a neutral arc system, but with time the flexure-hinge retreat of the lower plate largely exceeded the amount of convergence. Consequently, backarc extension took place, accompanied by high-rate forward migration of the thrust belt-foredeep system. Referring to the post-Tortonian evolution of the Apennines, the progressive opening of the Tyrrhenian Sea and the synchronous forward migration of the Apennine thrust-and-fold belt, accompanied by consumption of the Adria foreland, are the most striking results of these processes. At present, the Apenninic chain appears to be divided into two major arcs: the Northern Apenninic Arc and the Southern Apenninic Arc, the latter including the Calabrian Arc. This configuration (PATACCA and SCANDONE, 1989) has been related to a first-order segmentation of the subducting lower plate (see ROYDEN *et al.*, 1987), with major free boundaries which have accommodated the differential flexure retreat of the sinking lithosphere. High-rate (≥ 5 cm/year) roll-back processes in the Southern Arc (see MALINVERNO and RYAN, 1986; PATACCA and SCANDONE, 1986, 1989; PATACCA *et al.*, 1990) account for the generation of new oceanic lithosphere in the Southern Tyrrhenian basin (FINETTI and DEL BEN, 1986; SARTORI, 1990) and for the presence of a deep Wadati-Benioff zone at the rear of the Calabrian Arc (ANDERSON and JACKSON, 1987b; GASPARINI *et al.*, 1982; GIARDINI and VELONÀ, 1991).

The northern, northeastern and southwestern margins of the present Adria microplate are well defined by the Western Alps-Southern Alps, Dinarides and Apennines, respectively. The southern continuation of the microplate, on the contrary, is still a matter of debate. Geodetic and stress field investigations in the Central Medidterranean region (MONTONE *et al.*, 1997; MÜLLER *et al.*, 1992; RAGG *et al.*, 1995; WARD, 1994) suggest that Southern Sicily belongs to the Africa plate and is moving NW with respect to Europe. Conversely, the same types of data indicate that Apulia is moving NE at high angles with the slip vectors describing the Africa motion (see ANZIDEI *et al.*, 1997; WARD, 1994). Several rotation poles of Adria versus Europe and of Africa versus Europe are available in the geological literature (Tables 1 and 2). In this paper we propose a new rotation pole of Adria versus Europe, located some tens of kilometres SW of Genoa, which in our opinion

Table 1

Rotation poles of Adria versus Europe

Reference	Lat.	Long.
Anderson and Jackson (1987a, b)	45.8	10.2
Westaway (1990)	44.5	9.5
Ward (1994)	46.8	6.3
This work	44.2	8.3

better fits the bulk of the geological information as well as the available VLBI data from Matera station (Ward, 1994) and the fault plane solutions of major earthquakes along the outer margin of Adria from the Western Alps to the Western Hellenides (Dziewonski *et al.*, 1983 and subsequent fault plane solutions available in the CMT computer file catalogue; Eva *et al.*, 1997; Herak *et al.*, 1995; Muco, 1994; Papadimitriou, 1993; Renner and Slejko, 1994). According to this reconstruction, the Ionian Sea is part of the present-day Adria microplate whose sinking slab is shown by the South-Tyrrhenian Wadati-Benioff zone (Anderson and Jackson, 1987b; Gasparini *et al.*, 1982; Giardini and Velonà, 1991) and by the Aeolian calc-alkaline volcanic arc (Serri, 1997). The Malta Escarpment, reaching in the north the active Etna volcano (Hirn *et al.*, 1997) and forming the most striking morphotectonic feature of the region (Scandone *et al.*, 1981), appears to be the best candidate for transtensional plate margin between Africa (Southern Sicily) and Adria (Ionian Sea).

The Sicilian Maghrebides (Lentini *et al.*, 1996) represent the natural westward continuation of the Apennines. Nevertheless, their structure and kinematic evolution are quite different from the Apennines because the Sicilian orogenic segment has evolved, starting from Late Tortonian-Messinian times, as a transpressional

Table 2

Rotation poles of Africa versus Europe

Reference	Lat.	Long.
McKenzie (1972)	22.7	−28.2
Dewey *et al.* (1973)	31.3	−34.7
Minster and Jordan (1978)	25.5	−21.2
Chase, 1978	29.2	−23.5
Searle (1980)	21.3	−21.0
Livermore and Smith (1985)	22.7	−31.9
Anderson (1985)	27.6	−19.7
Helman (1989)	0.6	−15.8
De Mets *et al.* (1990)	21.0	20.6
Westaway (1990)	21.0	−21.0
Ward (1994)	−7.7	−57.1

belt accreted between the northwestward moving Africa margin (Africa-Europe convergence) and the eastward-escaping Calabrian Arc (roll-back of the subducting Ionian lithosphere).

3. Base Data and Geological/Geophysical Constraints for Seismotectonic Analysis

The seismotectonic analysis of the Italian territory is basically founded on GIS-aided cross correlation of three data sets concerning:

- the 3-D structural model of Italy and surrounding areas;
- the space distribution of historical and present seismicity;
- the kinematic model of the Central Mediterranean region, referred to the last 6 million years and including the available information on the present-day plate motion and stress field.

Figure 3 is a flow chart explaining the research activities which led to the construction of the seismotectonic model of Italy.

The structural model allows us to recognise and define lateral inhomogeneities both in the crust and in the mantle, to establish the geometry of the potentially active structures and to evaluate the mechanical characteristics of the rocks at

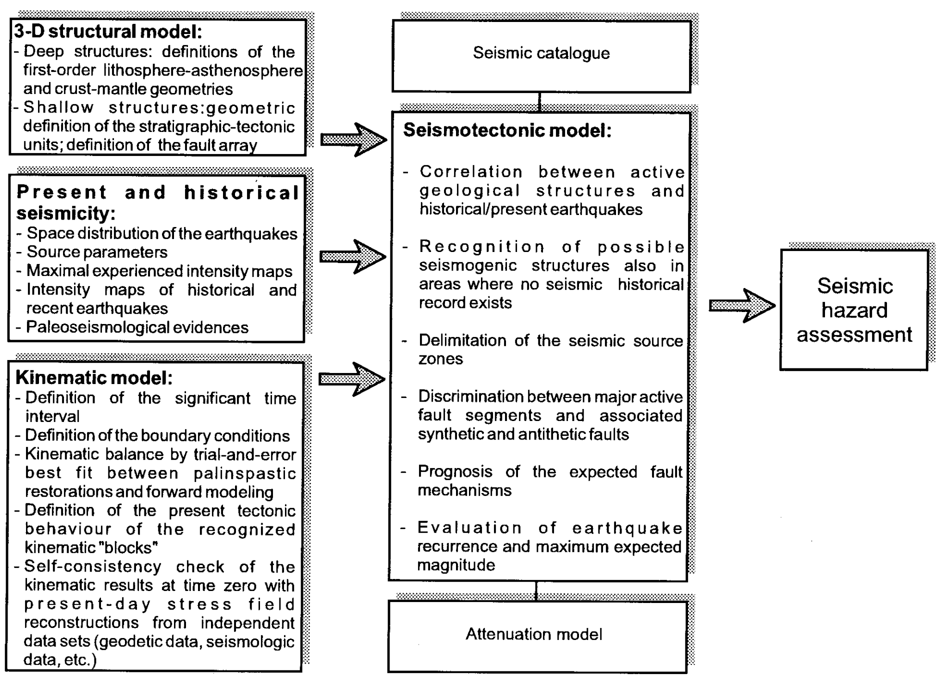

Figure 3
Flow chart of the research activities which led to the seismotectonic modelling of Italy.

different depths. Owing to the different investigation techniques, the model resolution is obviously different going from the lithosphere/asthenosphere boundary to the upper crust (see CHIARABBA and AMATO, 1996; CNR, P.F. GEODINAMICA, 1990; NICOLICH, 1989; SUHADOLC and PANZA, 1989). As regards shallow depths ($\leq$ 10–15 km), the information has been improved by commercial seismic lines and exploratory wells.

The basic documents we used to analyse the earthquake distribution and to correlate seismicity and active geological structures are principally represented by the ING Catalog (ING, 1995) as regards the present-day seismicity, the CNR-Progetto Finalizzato Geodinamica Catalog (POSTPISCHL, 1985) which covers the 1000–1980 time interval and the NT Catalog (CAMASSI and STUCCHI, 1996), a new declustered catalog currently adopted for hazard evaluations in Italy. Other important pieces of information are represented by a map of the maximal experienced intensities in Italy (MOLIN *et al.*, 1996) and by the intensity maps of several hundred historical and recent earthquakes which have struck the territory over the last 2000 years (MONACHESI and STUCCHI, 1997; BOSCHI *et al.*, 1995a, 1997). The macroseismic field reconstructions were very useful for constraining the seismotectonic model and for delimiting the seismic source zones. In several cases close correlations between active geological structures and earthquakes were found; in other cases the existence of an accurate macroseismic documentation forced us to better explore areas where no active faults had been previously recognized. In some cases, finally, the absence of earthquake documentation in areas characterized by severe recent deformation suggested the need for improvements in the historical research, as well as new plans for accurate paleoseismological investigations.

A kinematic model based on reliable palinspastic restorations provides the time/space trend of several independent and dependent variables (e.g., rate of flexure-hinge retreat of the subducting lithosphere, migration rate of the compressional and extensional fronts, tectonic subsidence and uplift, slip rates along active faults, etc.) which may be very important for seismotectonic investigations. The availability of well-calibrated curves representing the time-space variation of these parameters, in fact, allows us to better control the extreme points of the functions at time zero, that is, it enables us to better understand the present-day tectonic activity and, in addition, to recognize possible changes of the geodynamic regime. Moreover, a reliable kinematic model may establish first-order boundary conditions that force us to reconsider unquestioned postulates and sometime to abandon them as out of data opinions. The most striking example concerning the last point is represented by the Apenninic "paradox." From Eastern Liguria to the Calabrian Arc the Apennines border the southwestern margin of the subducting Adria plate. Consequently, the Adria margin in this region has usually been described as a converging plate margin. However, if we consider the north and northeastern margins of the same microplate, we see that it is also bordered by compressional features which point to another converging plate boundary extended from the

Western Alps to the Western Hellenides. The geometry and kinematic evolution of the Circum-Adriatic thrust-and-fold belts, on the other hand, cannot be explained as a result of the crashing of the Adria microplate between the Africa and Europe major plates. The results of the kinematic analysis, in addition, demonstrate that Adria has undergone counterclockwise rotation at least since Neogene times, and this motion implies extensional and not compressional slip vectors across the southwestern margin of the microplate. If this reconstruction is correct, how and why did a contractional belt take place in the Apennines while synchronous thrust-and-fold belts developed in the Southern Alps and Dinarides? The kinematic paradox is only apparent if we take into account that the tectonic style changed across the inner margin of Adria from a neutral arc system to an arc/backarc system. This change implies that the rate of the flexure-hinge retreat in the lower (Adria) plate largely exceeded the convergence rate and caused the opening of a backarc basin. The relationships among the principal kinematic parameters are expressed by:

$$V_{\mathrm{ext}} = V_{\mathrm{flr}} - V_c$$

where V_{ext} is the extension rate in the backarc basin (higher than 5 cm/year in the Southern Tyrrhenian Sea), V_{flr} is the velocity of flexure-hinge retreat in the lower plate and V_c is the Europe-Adria plate convergence rate. The rate of migration of the thrust belt-foredeep system towards the foreland areas roughly equals the rate of the flexure hinge retreat of the lower plate. In a regime of passive slab sinking (which is expected in west-dipping subductions, see DOGLIONI, 1991), flexure-hinge retreat may also continue under negative values of the convergence rate; the only difference in the kinematic balance is represented by the fact that the increase of source area absorbed by the overall extension in the backarc basin is transferred as sink area at the outer margin of the diverging plate. In conclusion, the kinematic analysis shows that the post-Tortonian Apenninic compression did not take place along a converging margin but along a diverging one, while the Southern Alps and Dinarides developed along a converging margin. In our opinion, the Apenninic "paradox" may be justified not only in terms of kinematics, but also in terms of mechanics by the geometry and dynamics of the lithosphere-asthenosphere system. The deep structure of the mountain chain, in fact, shows that the shallow asthenosphere occupying the space between the upper plate and the decoupled lower plate (MARSON *et al.*, 1995; SUHADOLC *et al.*, 1993) may act as a pushing back-stop of the contractional system driven by the passive lithosphere sinking (MELETTI *et al.*, 1995). Figure 4 shows a schematic lithospheric section across the Northern Apenninic Arc in which the edge of the deep-seated asthenospheric wedge plays the role of the leading edge of the shallow thrust system.

It is interesting to note that the kinematic analysis suggests a persistence of the described geodynamic regime in the Northern Apenninic Arc and probably in the Calabrian Arc, while it exhibits a dramatic change in the Southern Apennines

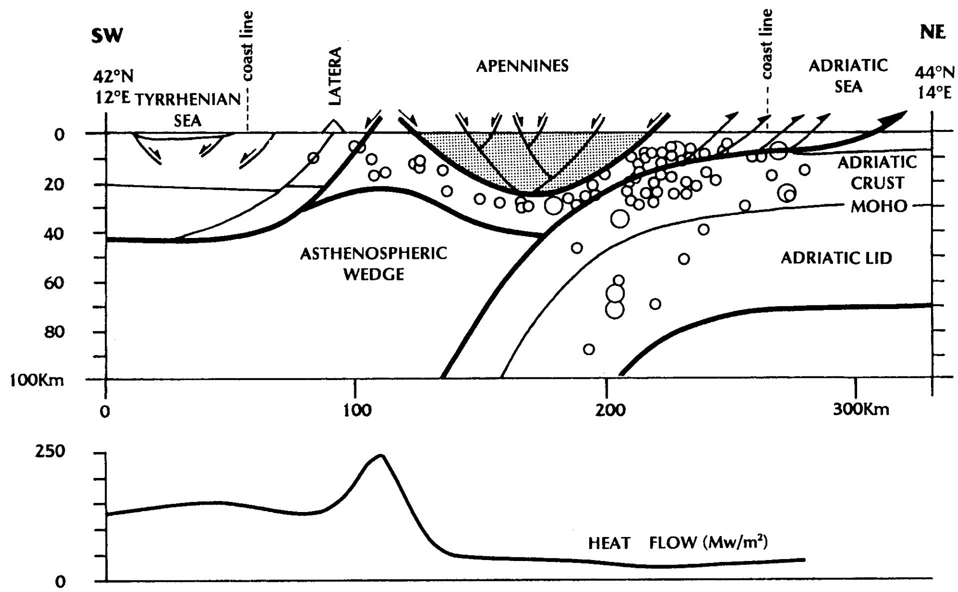

Figure 4
Schematic lithospheric section across the Northern Apenninic Arc (after MELETTI *et al.*, 1995).

(CINQUE *et al.*, 1993; HIPPOLYTE *et al.*, 1994) which took place near the base of the Middle Pleistocene. In this region a model similar to the one in the Northern Apennines has recently been proposed by DOGLIONI *et al.* (1996). We disagree as regards this model because the available geological information indicates that the flexure-hinge retreat suddenly ceased around 0.65 Ma (slab detachment?) from Eastern Abruzzi to Southern Basilicata and a generalized uplift of the mountain chain followed, accompanied by a regional tilting of the whole edifice towards the NE and by normal faulting along the Tyrrhenian slope. At present, active faults roughly follow the orographic divide of the mountain chain in an extensional stress field characterized by NE-SW oriented T-axes (AMATO and MONTONE, 1997; MONTONE *et al.*, 1997). We have interpreted (PATACCA *et al.*, 1997) this extensional stress field as the consequence of an early stage of rifting, related to the counter-clockwise rotation of Adria, which began to happen approximately 0.65 Ma after the subduction processes stopped in the Southern Apennine segment.

4. Seismotectonic Model and Seismic Zonation

Figure 5 represents a structural/kinematic sketch of the Italian peninsula and surrounding areas which shows the first-order tectonic structures. The following major elements have been indicated:

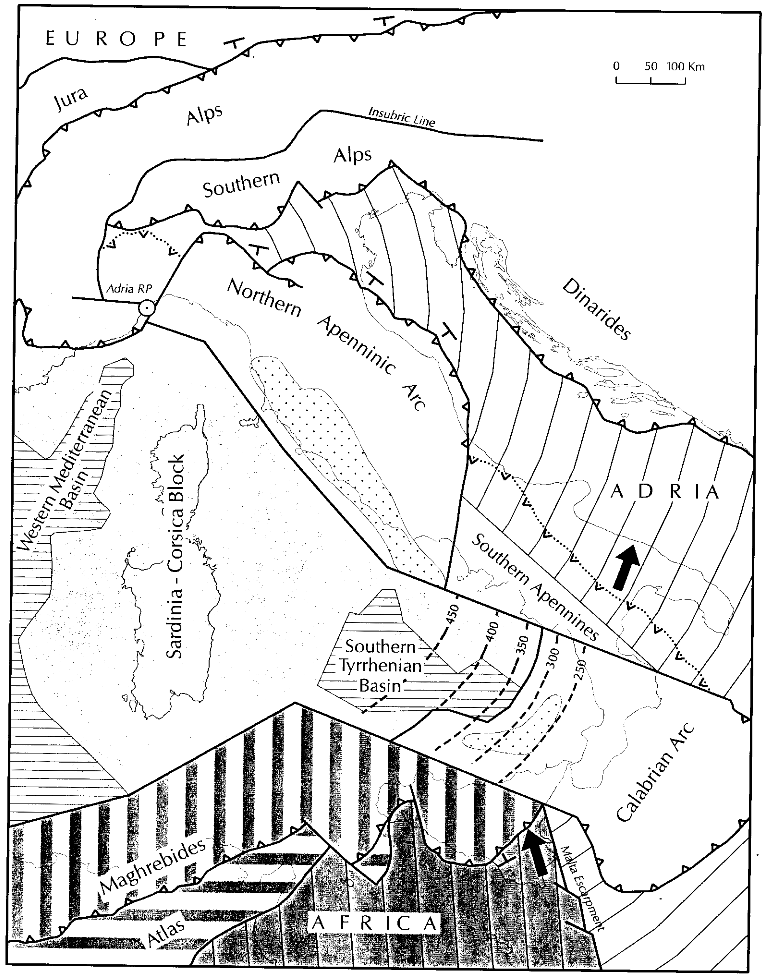

Figure 5
Structural/kinematic sketch of Italy and surrounding areas showing the traces of the slip vectors of Africa versus Europe (according to LIVERMORE and SMITH, 1985) and Adria versus Europe (according to the rotation pole proposed in this paper). See explanation in the text.

– the Adria microplate and the traces of the slip vectors describing its motion towards Europe;
– the rotation pole of Adria (Adria RP);
– the northern portion of the Africa plate and the traces of the slip vectors describing the Africa-Europe convergence. Black arrows represent the slip vectors at Matera (Adria) and Noto (Africa) stations according to WARD (1994);
– the European plate, including the Corsica-Sardinia block as well as the Western Mediterranean and the Tyrrhenian backarc basins;

– the Malta Escarpment, interpreted as the plate boundary between Africa and Adria;
– the thrust-and-fold belts, together with the major lithospheric free boundaries;
– the shallow asthenospheric wedges (dotted areas) in the Northern Apenninic Arc and the Calabrian Arc;
– the compression front of the Europe-verging Alpine system;
– the compression fronts of the Adria-verging outer thrust systems (Southern Alps, Dinarides);
– the Insubric Line, roughly separating the Europe-verging Alpine nappes from the Adria-verging thrust sheets of the Southern Alps;
– the compression fronts of the Adria-verging inner thrust system (Northern Apenninic Arc and Calabrian arc). The compression front is inactive in the Southern Apennines;
– the extensional young fault system between the Adria and Europe plates in the Southern Apennines;
– the Wadati-Benioff zone of the Southern Tyrrhenian Sea;
– the compression front of the Africa-verging Maghrebides.

Figures 6 and 7 show the present-day and historical earthquakes plotted on the geological features of Figure 5.

In the proposed seismotectonic model, the earthquakes bordering the outer margin of Adria are attributed to thrusts and to transpressional faults, all related to the counterclockwise rotation of Adria versus Europe. Due to the position of the rotation pole, the slip vectors obviously increase from the Western Alps to the Dinarides under the same angular velocity. As regards Italian territory, maximum shortening and maximum seismic potential are expected north of the Venice Gulf, in accordance with present and historical seismicity.

Conversely, no plate convergence may be invoked in order to explain the observed seismicity in the Apennines. In the Northern Apenninic Arc, the slab sinking with a flexure-hinge retreat faster than the Adria divergence may wholly justify the regional seismicity pattern characterized by:
– low/medium-energy compressional earthquakes along the Padan-Adriatic margin of the Apennines related to active frontal and lateral ramps which branch off from the sole-thrust at greater and greater depths (but in any case not exceeding about 20 kilometers) moving from the foreland towards the mountain chain;
– medium/high-energy earthquakes, mostly displaying extensional dip-slip focal mechanisms, in correspondence to an axial belt located between the Adria flexure-hinge and the Tyrrhenian asthenospheric wedge. The bulk of the focuses is contained in a crustal synform where the opposite geometries of the rising Tyrrhenian asthenosphere and the sinking Adria lithosphere are accommodated (see Figs. 1 and 2) by NE-dipping low angle master-faults and SW-dipping high-angle antithetical-faults (BARCHI *et al.*, 1996; BONCIO *et al.*, 1996; MELETTI *et al.*, 1995);

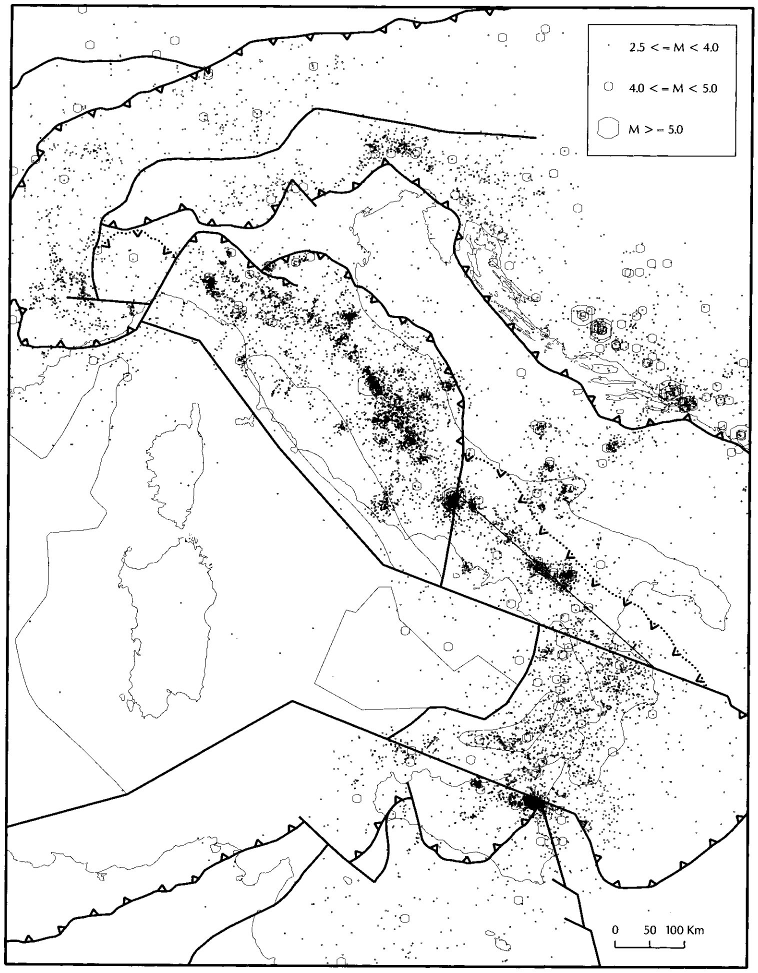

Figure 6
Present-day seismicity plotted on the sketch of Figure 5. Seismicity from ING (1995).

– low-energy very shallow earthquakes above and behind the mobile asthenospheric wedge.

In the Southern Apennines, the cessation of subduction while the counterclockwise rotation of the Adria microplate was still continuing produced a strong modification of the lithosphere-asthenosphere system and the establishment of an extensional regime. A seismic axial belt is present, characterized by medium/high-energy earthquakes whose available focal solutions show dip-slip mechanisms. We relate the seismicity of the Southern Apennines to very young normal faults generated by the Adria divergence, superimposed on inactive contractional structures.

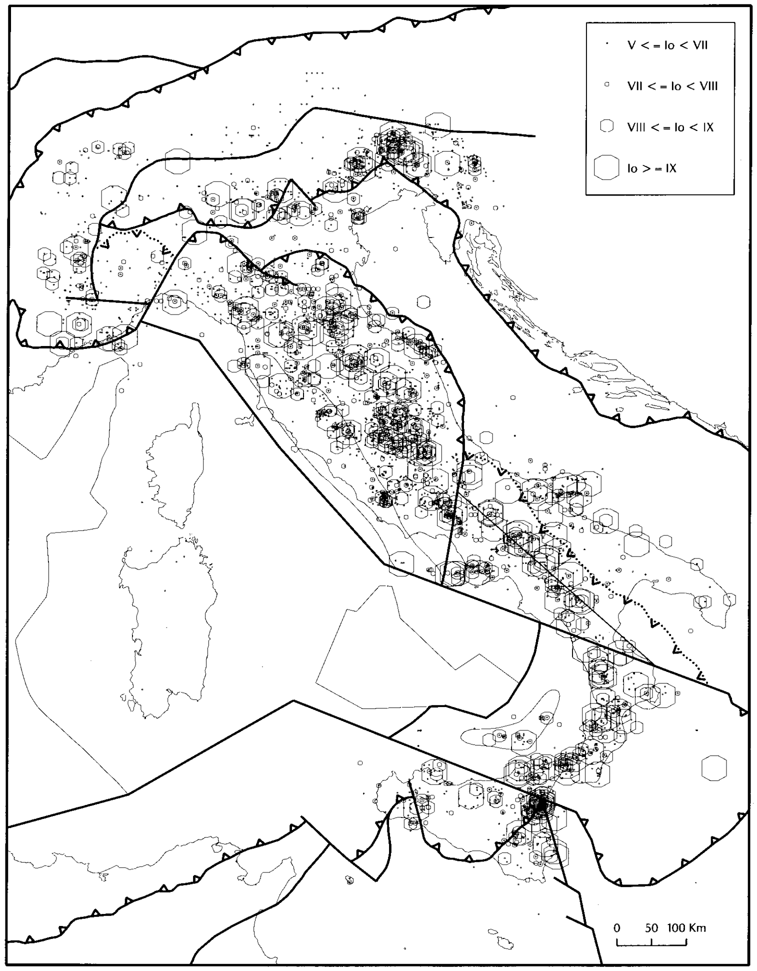

Figure 7
Historical seismicity plotted on the sketch of Figure 5. Seismicity from POSTPISCHL (1985).

The present-day behaviour of the Calabrian Arc is a matter of debate. Due to conflicting geological/geophysical evidence, it is not clear whether the well-known Wadati-Benioff zone of the Southern Tyrrhenian Sea is still attached to the Ionian lithosphere or if it represents a recently detached slab. In the first case we would expect an active flexure-hinge retreat, accommodated by two major free boundaries at the northern and southern terminations of the arc expressed at the surface by a sinistral strike-slip fault system and by a dextral one, respectively. In effect these systems exist where they are expected (MORETTI *et al.*, 1994; NERI *et al.*, 1996), but we are not sure whether they presently act as major free boundaries. A serious element of doubt is represented by the absence of shallow earthquakes with thrust mechanisms in the Calabrian-Arc Ionian offshore, where they would be expected in the case of a persisting flexure-retreat. On the other hand, the major extensional features on land, from the Crati to the Mesima valleys, closely follow the elongation of the mountain belt and the reconstructed stress field shows extension axes normal to the dip of the sinking slab (GUERRA *et al.*, 1981; MONACO *et al.*, 1996; TORTORICI *et al.*, 1995). T axes with NE-SW direction, on the contrary, would be expected in the event that Calabria underwent the same evolution as the Southern Apennines. In conclusion, we prefer the first hypothesis, although we cannot exclude that the Calabrian Arc is presently experiencing the same change of geodynamic regime which took place in the Southern Apennines 650 Kiloyears ago. Following this choice, we consider the longitudinal extensional structures of Calabria as the equivalent of the extensional features in the axial belt of the Northern Apenninic Arc. In the hypothesis that the rate of flexure-hinge retreat has not remarkably decreased with respect to Lower-Middle Pleistocene times, we should expect in Calabria slip rates considerably higher than in the Northern Apennines, in accordance with the historical seismicity of the region.

The seismotectonic interpretation of the Calabrian Arc obviously influences the interpretation of Northern Sicily where a dextral transpressional shear zone is expected, compatible with the seismicity pattern of the area.

In Southern Sicily the geological picture is quite different, the active-fault pattern being dominated by the first-order NNW-SSE Malta fault-system and by a second-order NE-SW fault system related to the flexure of the Hyblean Plateau. An important free-boundary in Western Sicily accommodates the differential foreland flexure-retreat, maximum at the northwestern margin of the Hyblean Plateau and minimum in the Sciacca zone. We attribute the seismicity of Western Sicily (see 1968 Belice earthquake, $M = 5.9$) to the activity of this tear fault.

The active tectonics of the Gargano-Tremiti and Central Adriatic region is still poorly understood, in spite of the rich information coming from off-shore oil exploration. An inversion active tectonics (ARGNANI *et al.*, 1993; FAVALI *et al.*, 1993), with remobilization of previous extensional faults in a compressional/transpressional regime, seems to be a likely working hypothesis.

Returning to the seismotectonic model of the entire national territory and adjacent areas, we see that the seismicity pattern is controlled within a relatively small space by a very complex geodynamic framework. Within this framework we can recognize:

– continent–continent convergence (Alps and Dinarides) with development of compressive-transpressive features along the plate margins;
– plate divergence across margins characterized by passive slab sinking (Northern Apennines and Calabrian Arc), with development of backarc basins (Northern Tyrrhenian Sea and Southern Tyrrhenian Sea) flanked by forelandward migrating thrust belt-foredeep systems;

– plate divergence across a margin previously characterized by lithosphere sinking and thereafter discharged from the subducted slab (Southern Apennines), with development of quite peculiar rift processes within the inactive thrust belt;
– transpression (Northern Sicily) due to the combined effect of plate convergence (Africa-Europe) and high-rate flexure-hinge retreat of an intervening plate (Adria microplate) with high angles between the respective slip vectors;
– intraplate strain partition and fault activity (mainly combined strike-slip and thrust motions), possibly in correspondence to inverted structures.

Within the single mobile belts the earthquake space distribution and the maximum source dimensions are obviously controlled by the overall geometry of

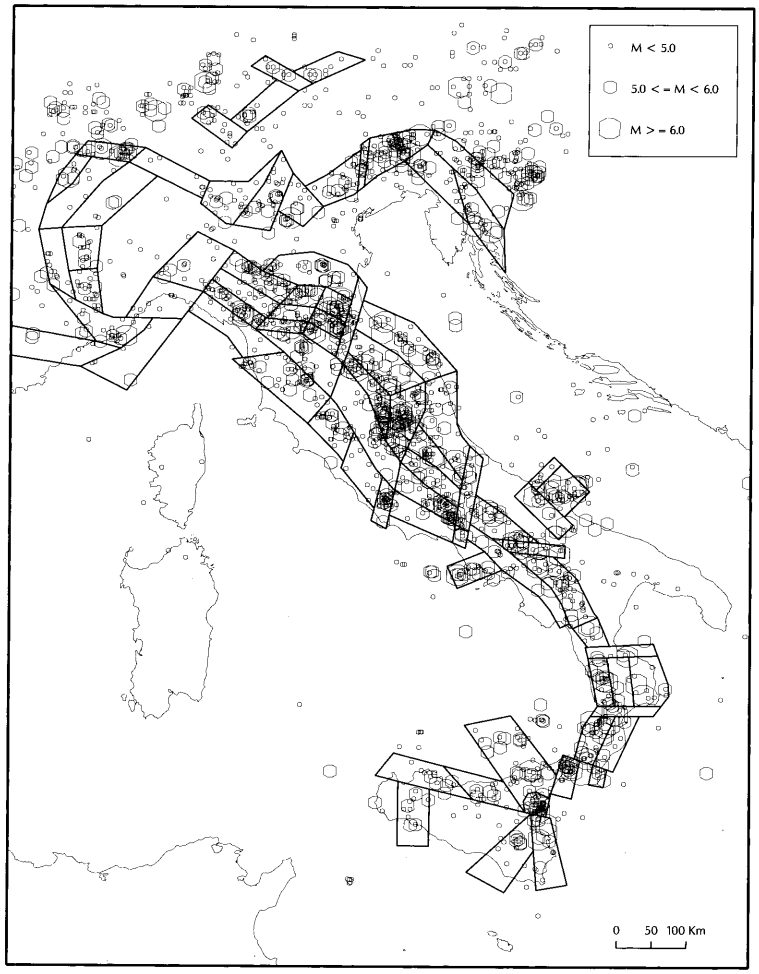

Figure 8
Seismic zonation of Italy and earthquake epicenters according to the NT Catalogue (Camassi and Stucchi, 1996).

the system (3-D structural model), while the slip rate and the focal mechanisms are determined by the kinematics of the mobile lithosphere-asthenosphere system (kinematic model). Figures 8 and 9 and relative captions summarize the present-day state of the art regarding the seismic zonation of Italy.

5. Concluding Remarks

We wish to underline that the zonation described is subject to periodic revisions and improvements. A new version is currently in progress within the framework of the activities of CNR-National Group for Defense against Earthquakes. Due to the absence of standard methodologies in regional seismotectonic analyses, we were forced to make basic choices and we preferred the kinematic approach, owing to its implicit multidisciplinary content. Results have reinforced our opinion that a structural/kinematic analysis represents a useful tool to reach the first seismotectonic goal, that is to understand where and why destructive earthquakes occur in a certain region and what kind of mechanisms are expected. Other approaches, in particular those of classical geomorphological and paleoseismological nature, are not considered alternative to the structural/kinematic approach but integrative,

Figure 9

Kinematic behaviour of the seismic source zones of Italy. a. Zones related to the Adria-Europe convergence. Expected mechanisms: prevailing thrust with *P* axes following the Adria slip vectors (zones 4, 6, 8, 16–21); NW-SE dextral transpression (zones 1–3); W-E and WNW-ESE dextral (zones 10, 15) and sinistral (zone 22) strike-slip; N-S sinistral strike-slip (zone 5); mixed thrust and strike-slip mechanisms (zone 9). b. Alps-Apennine transfer zones and Ligurian Sea. Expected mechanisms: sinistral strike-slip in shallower crustal structures and dip-slip in deeper crustal structures (zones 23, 25, 26); compression (thrust and sinistral strike-slip with W-E and WNW-ESE *P* axes) overprinting previous extensional features (zone 24). c. Zones related to the passive sinking of the Adria lithosphere beneath the mountain chain in the Northern Apenninic Arc. Expected mechanisms: thrust and strike-slip with SW-NE *P* axes in the Adriatic longitudinal belt (zones 30, 35, 38, 48, 53); mostly dip-slip with SW-NE *T* axes in the axial belt (zones 28, 29, 32–34, 36, 37, 44–47, 50–52); prevailing NNE-SSW dextral strike-slip and subordinate dip-slip (deeper crustal structures) in transfer zones (40, 55); dip-slip with SW-NE *T* axes in the Tyrrhenian longitudinal belt (zones 27, 31, 41, 42, 49, 54) with possible NNE-SSW dextral strike-slip. d. Zones related to the deactivation of the thrust belt-foredeep system in the Southern Apennines and to the counterclockwise rotation of Adria. Expected mechanisms: dip-slip with SW-NE *T* axes (zones 57, 58, 62–64). e. Zones of the Calabrian Arc, probably related to the persisting passive sinking of the Adria lithosphere. Expected mechanisms: dip-slip with W-E and WNW-ESE *T* axes in the longitudinal structures (zones 66, 67, 69–72); W-E sinistral strike-slip (zones 65, 68); WNW-ESE dextral transpression (zones 75, 76); NW-SE dextral strike-slip (zone 74). f. Zones related to the Africa-Adria divergence. Expected mechanisms: dip-slip along the Malta Escarpment and strike-slip along minor transfer faults (zone 79). g. Foreland zones with different kinematic behaviours. Expected mechanisms: flexure-related NE-SW dip-slip (zone 78); transfer-fault related N-S dextral strike-slip and possibly dip-slip in the deeper crustal structures (zone 77); thrust and strike-slip with *P* axes following the Adria slip vectors (zones 7 and 59–61). h. Zones in active volcanic areas. Expected mechanisms: dip-slip in the Ischia-Phlegrean Fields and Vesuvius region (zone 56); dip-slip and NW-SE dextral strike-slip in the Etna region (zone 73).

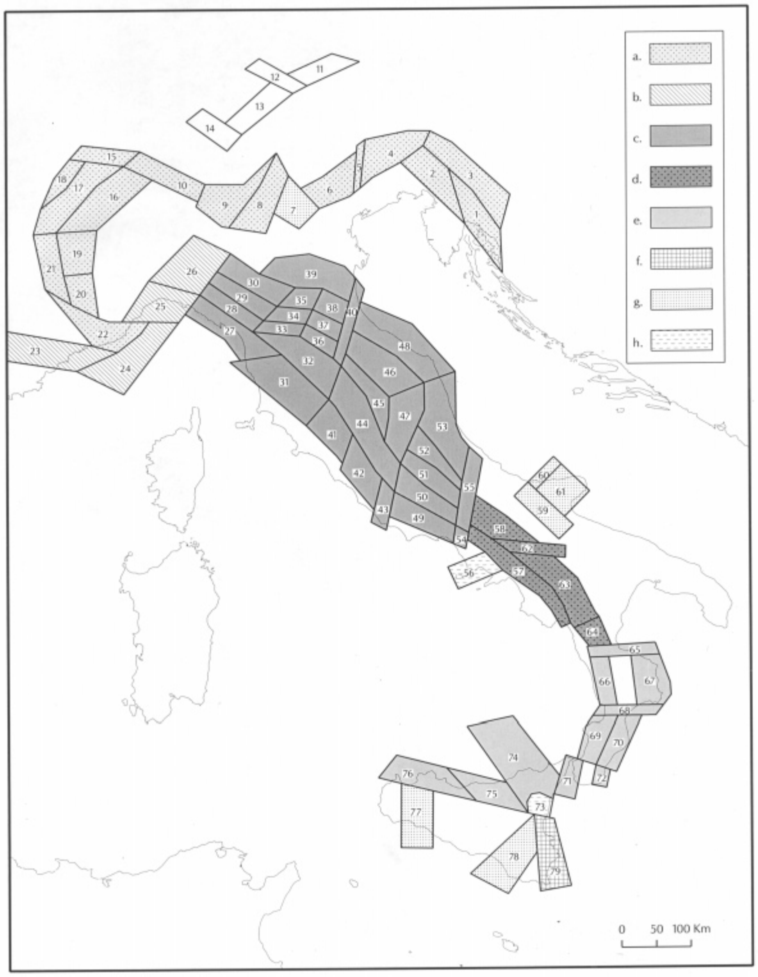

Fig. 9.

since they contribute to the characterization of the single seismic sources in terms of maximum expected magnitude, earthquake recurrence, etc. Obviously this is only a point of view.

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